THE UNIVERSITY OF CALGARY

Intermittently Operated Slow Sand Filtration: A New Water Treatment Process

by

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ABSTRACT

Access to potable water supplies is a great problem in the developing world. Many attempts have been made to develop a cheap, effective and robust way of treating water at a household scale but none have gained wide acceptance. In early 1991 Dr. Manz developed a hypothesis which would allow the adaptation of continuous slow sand filtration to intermittent use. After several studies which showed the effectiveness of filters operated in this way, this research was commenced to more closely examine intermittently operated slow sand filtration.

The investigation showed the filter is effective in removing 96% of faecal coliform indicators and that this can be further improved. A mathematical model of oxygen transfer into the filter bio-layer was developed and is supported by experimental data. Removals of contaminants occurred in two phases. First capture or interception and second, metabolism and consumption of contaminants. Design and operation recommendations may improve the effectiveness of future designs and identified possible areas for future research.

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FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance a thesis entitled "Intermittently Operated Slow Sand Filtration: A New Water Treatment Process" submitted by Byron James Buzunis in partial fulfilment of the requirements for the degree of Master of Engineering.

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u	-	settling velocity
g	-	acceleration due to gravity
ν	-	kinematic viscosity
ρ	-	density of the fluid
$\rho+\Delta\rho$	-	density of the particle
d_p	-	diameter of the particle
F_{O2}	-	mass flux of oxygen
C_s	-	saturation concentration of oxygen in water
C_B	-	concentration of oxygen just inside the air/water boundary
K	-	film constant
D	-	diffusion coefficient
∇	-	differential operator
C	-	concentration of oxygen in water
y	-	depth below water surface
C_L	-	concentration of oxygen at the bio-layer
y_L	-	depth of standing water layer
T	-	temperature

1.0 INTRODUCTION

Water, water, everywhere.../ Nor any drop to drink

- Samuel Taylor Coleridge

Access to potable water supplies is a priority for the developing world. More than two thirds of people in developing countries do not have access to safe drinking water (Pineo and Subrahmanyam 1975). The problem is especially bad in rural areas which cannot be connected with distribution systems. Often there is no access to potable water supplies for rural populations. A lack of technical knowledge concerning source protection and cultural practices, like communal washing of clothing, children and animals at water sources, has contributed to widespread contamination of water supplies (Lee 1991). It is estimated that 80% of the diseases in the world are associated with unsafe water (Huisman et al. 1981). So any improvement in water supplies will have a massive impact on the lives of people. Hippocrates (460-354 BC) knew the importance of water to health when he wrote "...whosoever wishes to investigate medicine properly should -consider the water the inhabitants use -for water contributes much to health" (Stein 1946).

In developed nations, like Canada, the safety of water supplies is taken for granted. This is not always the case. Often, rural water supplies are not biologically safe. In

fact, it has been recently discovered that small community supplies using only chlorination are not a totally effective barrier to cysts of *Giardia* and *Cryptosporidium* (Cleasby et al. 1984). It has also been found that private treatment systems and many of those operated for small communities do not receive the proper maintenance and do not have staff to operate them effectively (Tanner 1987). Sometimes the water treatment system fails and pathogens reach users placing them at risk. Even water treatment plants in major cities do not always remove or inactivate *Giardia* and *Cryptosporidium*. The City of Calgary is about to spend 76 million dollars to upgrade to its water treatment facilities in order to deal with this problem (Pritchard 1995).

Conventional slow sand filtration is a good solution for providing small communities safe water supplies in both developing and developed countries. Continuously operated slow sand filters are well suited to small utilities serving 25 to 3000 persons (Logsdon and Fox 1988). The benefits of slow sand filtration for developing countries are summarised by Gecaga 1980: " . . . (1) the cost of construction is low particularly when manual labour is used; (2) simplicity of design and operation means that filters can be built and used with limited technical supervision; (3) importing of materials and equipment can be negligible, and no chemicals are needed; (4) power is not required . . . because there are no moving parts nor requirements for compressed air or high pressure water; (5) variations in rainwater

quality and temperature can be accommodated . . . (6) water is saved because large quantities of wash water are not required; (7) sludge . . . is less troublesome."

During the 1980's a renewed interest developed in slow sand filtration among engineers in Canada and the United States. This was the result of slow sand filtration's simplicity of operation and its ability to remove *Giardia* and *Cryptosporidium* (Bellamy et al. 1985a, Bellamy et al. 1985b and Schuler and Ghosh 1991). Although used extensively in Europe, slow sand filtration has not been popular in North American. Rapid sand filtration (RSF) with coagulation is the treatment process of choice. Slow sand filtration has been, until recently, considered an old impractical technology even though little research has been done in the area since the turn of the century. The main disadvantages of conventional slow sand filtration are the large areas required, difficulties when operated with highly turbid waters and frequent cleaning caused by algae blooms (Huisman and Wood 1974). Still Huisman and Wood 1974 state "No other single process can effect such an improvement in the physical, chemical, and bacteriological quality of surface waters . . . "

The treatment efficiency of slow sand filters is indeed amazing considering the simple operation required. Virtually complete removal of indicator organisms and pathogens including bacteria, cysts, protozoa, viruses and helminths has been

shown by many researchers (Bellamy et al. 1985a, Bellamy et al. 1985b, Burman 1961, Burman and Lewin 1962, Cleasby et al. 1984a, Cleasby et al. 1984b, Ellis 1985, Foreman 1985, Fox et al. 1984, Hazen 1907, AWWA 1991, Huisman and Wood 1974, IRC 1987, Joshi et al. 1982, Joshi et al. 1985, Logsdon and Lippy 1982, McConnel 1984, Paramasavam et al. 1980, Schuler and Ghosh 1991, Visscher et al. 1987, Williams 1987). Because of its low cost, simple operations and effectiveness, conventional slow sand filters are considered an excellent way of providing safe water to small communities throughout the world, especially in developing countries.

Full scale continuous slow sand filters have been supplying potable water to communities for over 150 years (Scott 1956). A continuously operated slow sand filter is simply a container filled with fine sand with a means of adding water above the sand bed and underdrain to allow filtered water to be removed. Unlike rapid sand filters the main improvements in the quality of the water as it passes through the filter are the result of a biological layer which develops in the sand bed. These filters have water flowing through the sand bed continuously and the flow of water is only stopped for filter cleaning. The area covered by the filter is normally much more than 10 m^2 and is usually on the order of 1000 m^2. Figure 1.1 is a diagram showing the basic components of a continuously operated slow sand filter. Like most other water treatment processes, slow sand filtration is designed to

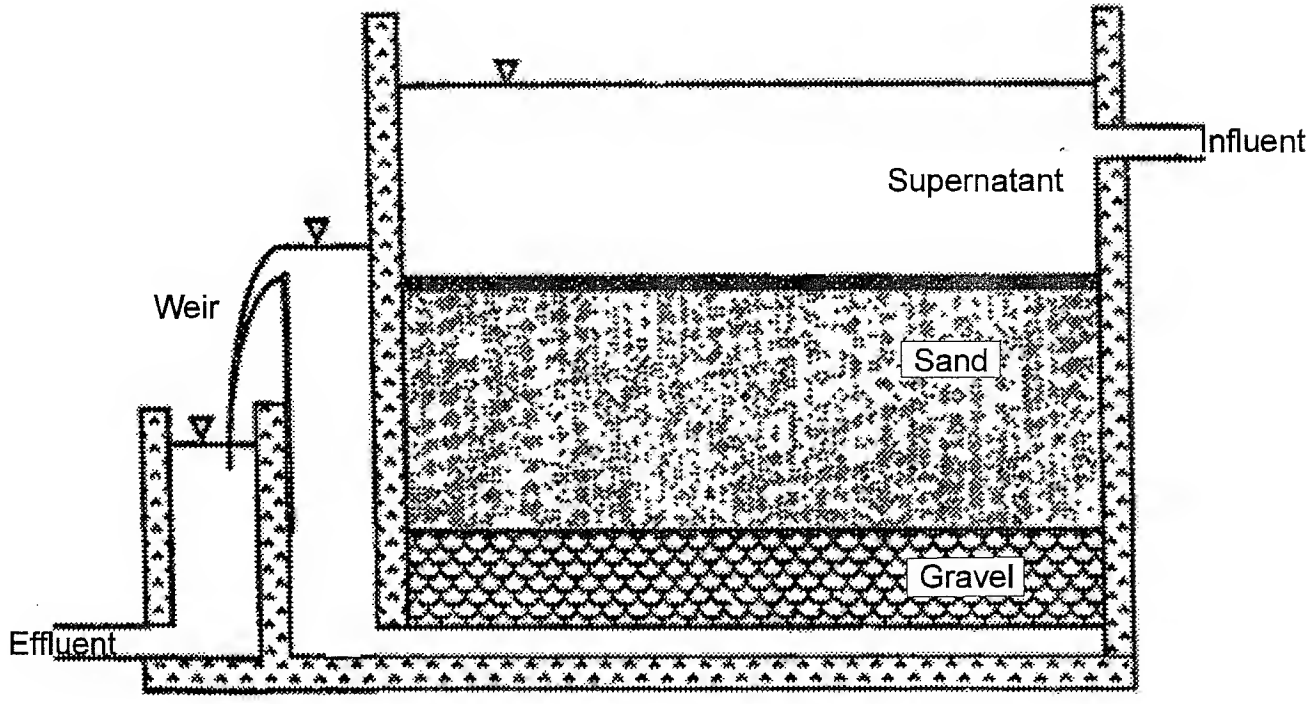

Figure 1.1 Basic Components of a Continuously Operarted Slow Sand Filter (after AWWA 1991)

be used with some sort of distribution system and is meant to supply water to a community of users.

Rural water supplies present significant problems for engineers. Dispersed populations are both expensive and difficult to supply with conventional distribution systems. Adequate quantities of water may be available but the expense of treating this water by conventional methods may be high and require highly trained personnel. In Canada and the United States, water is commonly trucked into acreages and farms. This type of water supply presents many opportunities for contamination and often an additional treatment system is used to provide potable water. Drilling a well is another solution but at a cost of nearly $30.00 Canadian per foot it rapidly becomes unattractive. The problems of supplying water in rural areas is compounded in the developing world where poverty and a lack of technical expertise make the solutions used in the developed world impossible and inappropriate. Sources that exist already have not been properly protected and managed so the great majority are contaminated. An intermittently operated, small scale slow sand filter would be an ideal solution for the water supply problems of dispersed rural populations. Processes which allow community sized slow sand filters to produce pathogen free water on an intermittent small scale have not yet been implemented. This is in part due to the general consensus in the current literature that is opposed to any variation in flow rates and vehemently states: ". . .

an intermittently operated slow sand filter will not be effective." (Vischer et al. 1987, Paramasivam et al. 1980)

The requirement for a household scale intermittently operated treatment systems is proven by the many treatment systems used in this way. Filtration systems like filtering through cheese cloth or other materials have been used for centuries to improve the aesthetic quality of water but provide little or no removal of pathogens. Boiling provides bacteriologically safe water but makes the water taste flat and uses much fuel. In developing countries fuel is scarce, expensive and the use of wood for fuel is a major cause of deforestation and environmental destruction. Also, wood fires contribute to respiratory problems because of a lack of proper ventilation. Chlorine is commonly used to disinfect water but often causes a taste that many find unpalatable (Lee 1991). In addition the doses of Chlorine required to disinfect surface waters are large and may not destroy cysts. Supplying chlorine to dispersed country settings is difficult where health care services are already overloaded.

Attempts to provide a small scale household water treatment system to supply potable water for drinking and cooking purposes are common, however, either the filtering material was very expensive, as with the silver impregnated Berkley filters (Wagner and Lanoix 1959), or they were designed and operated ineffectively, as

with household filters used by the World Health Organisation (WHO 1987). Other systems are simply inappropriate technology requiring significant technical knowledge and imported components. Still others are impractical, the removal of pathogens may be excellent but they are inconvenient and difficult for people to use. Systems of this type soon break down and the effort of installing them is wasted. Many proposed systems are only theoretically correct never having been piloted in the field or tested in any significant way before proposed as a solution to potable water problems in the developing world.

The need for a system of producing potable water at a household scale was also observed by David Manz during his development work in the Philippines and South Africa. The requirements of this type of water treatment system would be effective removal of pathogens and cultural acceptance. Soon after, Dr. Manz realised the similarities between what was being attempted by the various household sand filters and continuous slow sand filtration and developed the initial hypothesis that is the main component responsible for contaminant removal in continuous slow sand filtration is the biological layer. This process is aerobic and the sand must not be disturbed (Manz 1991).

1.1 Objectives

The objectives of this research program are first demonstrating the effectiveness of a small scale slow sand filter design which includes intermittent operation and small scale.

The second objective is to more fully develop and test a theory of IOSS filter operation that will describe and predict filter performance.

The third objective is to examine the effects of the filter on water quality and describe the operation and special characteristics of this design which makes it effective.

The fourth objective is to develop design recommendations which allow safe design of IOSS filters.

2.0 MECHANISMS OF FILTRATION

There's no limit to how complicated things can get,

on account of one thing leading to another.

- E. B. White

Filtration is the process of removing constituents from a fluid by passing the fluid through some type of media. Most commonly, this is thought of as a straining process similar to what occurs in a sieve. Particles that are larger than the openings in the filter are strained out. While straining is an important mechanism in filtration, there are several others that contribute to removals of particles much smaller than the pore openings in the media. The major differences between different filtration processes is due to the relative importance of different mechanisms of filtration.

Slow sand filters operate using all the mechanisms normally associated with filtration. Removal mechanism are classified into two general categories. Transport mechanisms which bring the particle into contact with the sand grain and attachment mechanisms which hold particles to the sand grain surfaces. These mechanisms include (Peavy et al. 1985):

- straining
- sedimentation

- inertial and centrifugal effects
- Brownian motion
- electrostatic forces
- van der Waal forces
- adhesion

More importantly, slow sand filters have additional removal mechanisms that are biological in nature which are classified as purification mechanisms (Huisman and Wood 1974, Visscher et al. 1987). These include:

- death and inactivation
- predation
- biological oxidation

The biological processes are the result of the formation of a biological layer that forms at the sand water interface and in the top 20 - 40 cm of sand (Bellamy et al. 1991).

2.1 Straining

After the initial start up there is a period of time when the physical mechanisms are mainly responsible for observed removals and are also mainly responsible for bringing substances into contact with the sand grains. Particles too large to fit between sand grains are strained out at the sand surface regardless of the rate of

filtration. In a bed of tightly packed spheres the pore openings will be one seventh the diameter of the spheres (Huisman and Wood 1974). This means that in a filter bed with effective sand size of 0.21 mm it can be expected that particles bigger than 0.03 mm or 30 μm will be strained out. This is not a perfect assumption since sand is not spherical and is graded over a range of sizes. As smaller particles are caught and accumulate the size of the pore openings at the sand surface is reduced allowing even smaller particles to be removed by straining. This layer of smaller particles that has been strained out at the surface is often referred to as the filter skin. The filter skin is the main contributor to head loss in slow sand filters and must be removed by scraping the top 1 - 2.5 cm of sand once head loss has become too high.

2.2 Sedimentation

Sedimentation in the supernatant and the sand bed itself is another major physical removal mechanism. Sedimentation occurs when particles simply settle out of the water. The size of particles which will be removed by sedimentation is a function of the settling velocity of the particle and the surface loading rate. The settling velocity of a particle can be determined by Stokes' equations for laminar settling (Huisman and Wood 1974):

$$u = \frac{1}{18}\frac{g}{v}\frac{\Delta\rho}{\rho}d_p^2 \qquad \text{Eq. 2.1}$$

where u is settling velocity, g is acceleration due to gravity, υ is the kinematic viscosity of the fluid, $\rho+\Delta\rho$ is the density of the particle, ρ is the density of the fluid and d_p is the diameter of the particle. At 20 °C the kinematic viscosity of water is 1.003×10^{6} m^2/s and the relative density of organic matter is typically 1.01 (Huisman and Wood 1974). Substituting these value into Equation 2.1 yields:

$$u = 5.291x10^{3} d_p^2 \ (m/s) \qquad \text{Eq. 2.2}$$

In addition sedimentation will partially remove particles smaller and lighter (Huisman and Wood 1974). The surface loading rate is the volume of water applied to each unit of area available for settling. The loading rate controls the time that a particle has to settle or reach a surface at the bottom of the basin. Each pore space in the sand bed acts as a miniature settling basin. Theoretically the entire upward facing surface area of the sand grains is available for sedimentation. In a cubic meter of sand, the area available for sedimentation easily exceeds 1000 m^2 (Huisman and Wood 1974) and probably is in the order of 10 000 m^2. A normal loading rate for slow sand filters is 0.2 $m^3/m^2/hr$ or 5.6×10^{-5} m/s. Every square meter of filter surface area is conservatively equivalent to 1000 m^2 of settling basin so the loading rate on the area available for sedimentation is actually 5.6×10^{-8} m/s. Substituting this in for u into Eq. 2.2 and solving for d_p yields:

$$5.29x10^{3} d_p^2 \geq 5.56x10^{-8} \qquad \text{Eq. 2.3}$$

$$d_p \geq 3.24\mu m \qquad \text{Eq. 2.4}$$

In a slow sand filter with a sand bed 1 meter deep and filtering at a rate of 0.2 $m^3/m^2/hr$, the calculation shows organic particles larger than 3.24 μm will be completely removed. The calculation however does not account for the increased effect of additional forces as particles become smaller. Sedimentation is very important for particles between 4 and 10 μm, but has little effect on colloidal particles, particles between 0.001 and 0.1 μm (Ellis 1985).

2.3 Centrifugal and Inertial Forces

Sedimentation brings particles into contact with the sand grains as a result of gravitational forces. Centrifugal and inertial forces also act to bring particles into contact with sand grains. Gravity flow through a porous media is normally assumed to be laminar in nature. If no external forces act upon a particle it will simply follow a stream line through the bed. However centrifugal forces and inertia cause the particle to leave the stream lines and collide with sand surfaces. A group of stream lines is defined as a stream tube. The fluid streamtubes in a sand bed follow a torturous root with many bifurcations and junctions. As a particle travels along in a streamtube the inertial effects may cause it to collide with a sand grain. Also, particles following a stream line passing near the surface of a sand grain may be too large to pass the sand grain without a collision. (AWWA 1991)

2.4 Brownian Motion, van der Waals Forces and Electrochemical Forces

Other mechanisms that act to bring particles into contact with sand grains include Brownian motion, van der Waal forces and electrochemical forces. Brownian motion is a random movement of small particles. These movements increase with increases in temperature. With each random move of the particle there is a chance that the particle may collide with a sand grain. Van der Waals forces and electrochemical forces are usually insignificant at distances above the molecular level. These forces are more important in attachment once the particle has reached the surface of the sand grain since they will not affect the particle until it is very near the surface of the sand grains.

2.5 Attachment Mechanisms, Adsorption

The attachment of particles to the sand grain allows the micro-organisms colonising the filter to break down organic materials and will retain inert materials until the filter is cleaned. Attachment to sand grains is the results of the several mechanisms usually classified under the broad heading of adsorption. These mechanisms include electrostatic attraction, van der Waals force, and adherence. (Huisman and Wood 1974)

Electrostatic attraction is the result of particles having opposite charges. Clean quartz sand and most bacteria are negatively charged while metallic ions and organic matter is positively charged. This is one reason a ripening period is required for slow sand filters since time is needed to allow the charges in the filter to accommodate attachment of the micro-biological life. (Huisman and Wood 1974)

Van der Waals forces interact with electrostatic attraction/repulsion to hold particles to the sand surface. Van der Waals attractive forces vary with the of distance between the particles and will exceed electrostatic repulsion of similarly charged particles at short distances (Peavy et al. 1985). This will allow like charged particles to attach to one another once a collision has taken place and the electrostatic repulsion has been overcome.

Adhesion is the result of bacteria growing on the organic materials deposited on the sand grains and at the sand surface, the schmutzdecke. The bacteria produce a slimy substance consisting of exocellular polymers and including living and dead cells. This substance is known as zoogeal (Brock and Madigan 1991). This substance is sticky and tends to retain and absorb particles which come into contact with it.

2.6 Purification Mechanisms

The biological mechanisms of removal are often referred to as purification mechanisms. Slow sand filtration is the only type of sand filtration that relies on aerobic biological processes to obtain high removals of contaminants. The first purification mechanism is death and inactivation. Generally micro-organisms require fairly specific environments in which to live. Most diseases, especially those that are transmitted by water, are adapted to live in the guts of warm blooded animals. The environment in a slow sand filter is not well suited to the lives of many pathogens. Because of the high number of microbes colonising the filter, food is scarce, much more scarce than in the intestines of a mammal. Also the temperature in the filter is generally much lower than what is optimal for these pathogens. In addition many organisms in the filter are predatory and feed on other cells. Finally cells living in the filter excrete chemicals that protect them from other microbes and viruses (Ellis 1985, Brock and Madigan 1991). The combined effects of this selectively hostile environment results in the death or inactivation of many pathogens.

2.7 Processes of Pathogen Removal and Inactivation

Pathogens removed by slow sand filtration include parasites, bacteria, protozoa and viruses. Parasites are normally some form of small animal which is removed primarily by straining at the water sand interface since they tend to be too large to fit into the sand pores.

Pathogenic bacteria and protozoa are removed mainly by death and predation. In the supernatant above the sand pathogens are preyed upon, exposed to light, and encounter the natural chemical protection of the organisms that have colonised this region. In addition, the temperature is normally too low for organisms used to 37 °C. Once the sandbed is reached the concentration of chemical protection increases due to increased populations of microbes and the concentration of food begins to rapidly decrease. Once a schmutzdecke has formed many of the larger particles will not pass through the decreased openings. If the pathogen makes it into the sand it starves due to lack of food in the filter (Huisman and Wood 1974).

Viruses are a different type of pathogen. They are able to replicate only by using the functions of a host cell. Viruses cannot replicate without a host cell. Viruses are removed mainly by adsorption and inactivation. The process of adsorption has been shown by McConnel 1984 to be a function of sand bed depth. Once attached, the

virus will be metabolised by microbes. Adsorption is also aided by the development of the zoogeal film on the schmutzdecke and the sand grains. However, active viruses were found by McConnel up to 1.02 m below the sand surface. In other studies the removal of viruses was attributed mainly to biological aspects of slow sand filters and more than 99% of the viruses introduced were removed in a 50 cm sand bed (Wheeler et al. 1988). The other process of virus removal is inactivation. Although the exact mechanisms are unknown, some inactivation can be attributed to the natural protection of the cells within the sand bed as well as the capacity of the sand to inactivate viruses.

3.0 WATER TREATMENT EFFICIENCY

Results! Why man, I have gotten a lot of results. I know several thousand things that won't work.

- Thomas Edison

The objective of water treatment processes is to make the water safe by removing, altering, or destroying those organisms and chemicals which may be harmful to people or equipment and to produce water which is aesthetically pleasing to users. Biologically speaking this means removing pathogens from the water. Pathogens include bacteria, viruses, and parasites. Innumerable diseases can be transmitted through water borne pathways. Cholera and typhoid fever are caused by bacteria. Viruses in water can cause polio and other diseases. *Giardia* is caused by a protozoa that forms hard to destroy cysts, and cerarcaie can be responsible for *schistosomiasis*. The majority of pathogens enter water through the faeces of animals and people infected with the disease. To determine if a water treatment process is performing as required it is important to measure how well it removes these disease causing agents.

3.1 Indicator Organisms

Testing for every conceivable pathogen in the water would be both time consuming and expensive. Working with infectious materials is also hazardous to the laboratory personnel and many times the concentrations of the pathogen in the water is so low that it may not be detected at all. Sometimes an accurate and reliable test for the pathogen in question does not even exist. Only when specific pathogens are suspected to be present will a test be considered. The rest of the time, indicator organisms are used to determine the biological safety of water and show the efficiency of water treatment processes.

An ideal indicator organism will have the following characteristics (Peavy et al. 1985):

- will indicate the nature and extent of the contamination
- be applicable to all types of water
- always be present if pathogens are present
- never be present if pathogens are not present
- be easy to test for and identify
- not be a pathogen

A group of organisms which satisfies most of these criteria is the coliform group of bacteria, and more specifically, faecal coliforms.

The coliform group of bacteria are mostly of intestinal origin although many species are found naturally in soil and vegetation, especially in tropical countries. They are defined as aerobic and facultatively aerobic, gram-negative, nonspore-forming, rod-shaped bacteria that ferment lactose with gas formation within 48 hours at 35 °C (multiple tube method) or produce a dark colony with a metallic sheen within 24 hours on an Endo-type medium containing lactose (membrane filter method) (APHA 1985).

Faecal coliforms are a more specific group of bacteria consisting of strains of *Escherichia, Klebsiella, Citrobacter* and *Enterobacter.* The strain *Escherichia* and mainly *Escherichia coli* are the main intestinal organisms with the other strains occurring to a lesser extent. These bacteria are enteric, meaning they live and multiply in the intestinal tracts of warm blooded animals. Faecal coliforms are separated from coliforms from non-faecal sources by using different growth medias and inhibitors and a higher incubation temperature of 44.5 °C. (Hutton 1983). The faecal coliform group is a good choice for an indicator organism because most water borne disease enters the water through the faeces of infected people or animals. Faecal coliforms behave similarly in water treatment processes to many pathogens. These factors also make them a good choice as an indicator of pathogens in water.

3.2 Criteria for Safe Water

Health agencies are responsible for maintaining and improving the health of the people in their jurisdictions. They do this by setting limits on the concentrations of chemicals and indicator organisms so that a high level of water quality will be maintained. Currently the World Health Organisation has set the limits of no more than 10 coliform bacteria in a standard 100 ml sample of water and no faecal coliform in a 100 ml sample for potable water supplies (WHO 1983). These limits are set with the idea that any contributor of faecal contamination to water may be a carrier of some disease which would also exist in the water.

3.3 Testing Methods

Testing for faecal coliform is normally performed by one of two techniques, both of which are accepted standards of Canadian and World Health Organisation Water Quality Guidelines. These are the Multiple Tube Method (MT) and the Membrane Filtration Method (MF). The MF technique was used in this research because of the following advantages (Dean 1992):

- Shorter incubation period required (24hr as opposed to 48-96hr)
- Less handling of samples.
- Simpler method requiring less training

- Fewer supplies required

- More precise

An outline of this method follows and the procedure followed is also described in Standard Methods (APHA 1985).

Initially samples were collected in sterile 250 ml polypropylene bottles. If tests were not conducted within 1 hour of sample collection the samples were refrigerated until the test. Based on previous tests of the same sampling point, sample dilutions were determined to give estimated plate counts of 20 - 80 colonies. The sample was then filtered through a 0.45 um pore opening membrane filter. The filter was part of a micro-biological monitor Sin-Can part no. 8025 which was used because it reduced the time required to conduct the test, sterilise equipment and also reduced the chances for error since no membrane transfers were needed. The faecal coliform counts for the intensive testing are averages of pairs of replicate plates. The media was then added to the micro-biological monitor. Media used in this experiment was made from dehydrated m FC Broth Base media produced by Difco. Media was prepared by following the instruction given on the label. Media consistency was insured by conducting overlap tests before beginning to use a new batch of media. The test plates were then incubated for 20 to 24 hours at 44.5 °C and counted.

Numbers obtained from membrane filter tests are not absolute numbers. Figure 3.1 shows the 95% confidence limits for plate counts between 0 and 100 faecal coliform

colonies as calculated from the formulas and tables given in Standard Methods (APHA 1985).

3.4 Characteristics of Pathogens in Water

3.4.1 *Bacteria*

Pathogenic bacteria cause several gastrointestinal diseases. The most well know and widely feared is cholera but bacteria are also responsible for hamburger disease, typhoid fever, salmonella and other diseases. Bacterial diseases transmitted by water normally cause diareha, a major cause of sickness in the developing world and a main cause of infant mortality.

Bacteria are much smaller than other micro-organisms. They are the smallest entity that has all the characteristics of life. Bacteria are usually between 1 and 5 μm long (Brock and Madigan, 1991), much smaller than the interstitial spaces between sand grains (10 - 20 μm). Bacterial cells are also nearly the same density as water. This means that straining and sedimentation have a limited ability to remove free living bacteria. Generally bacteria grow attached to surfaces, usually covering the surface of the particles. This type of growth is called a bio-film. Since bacteria are generally

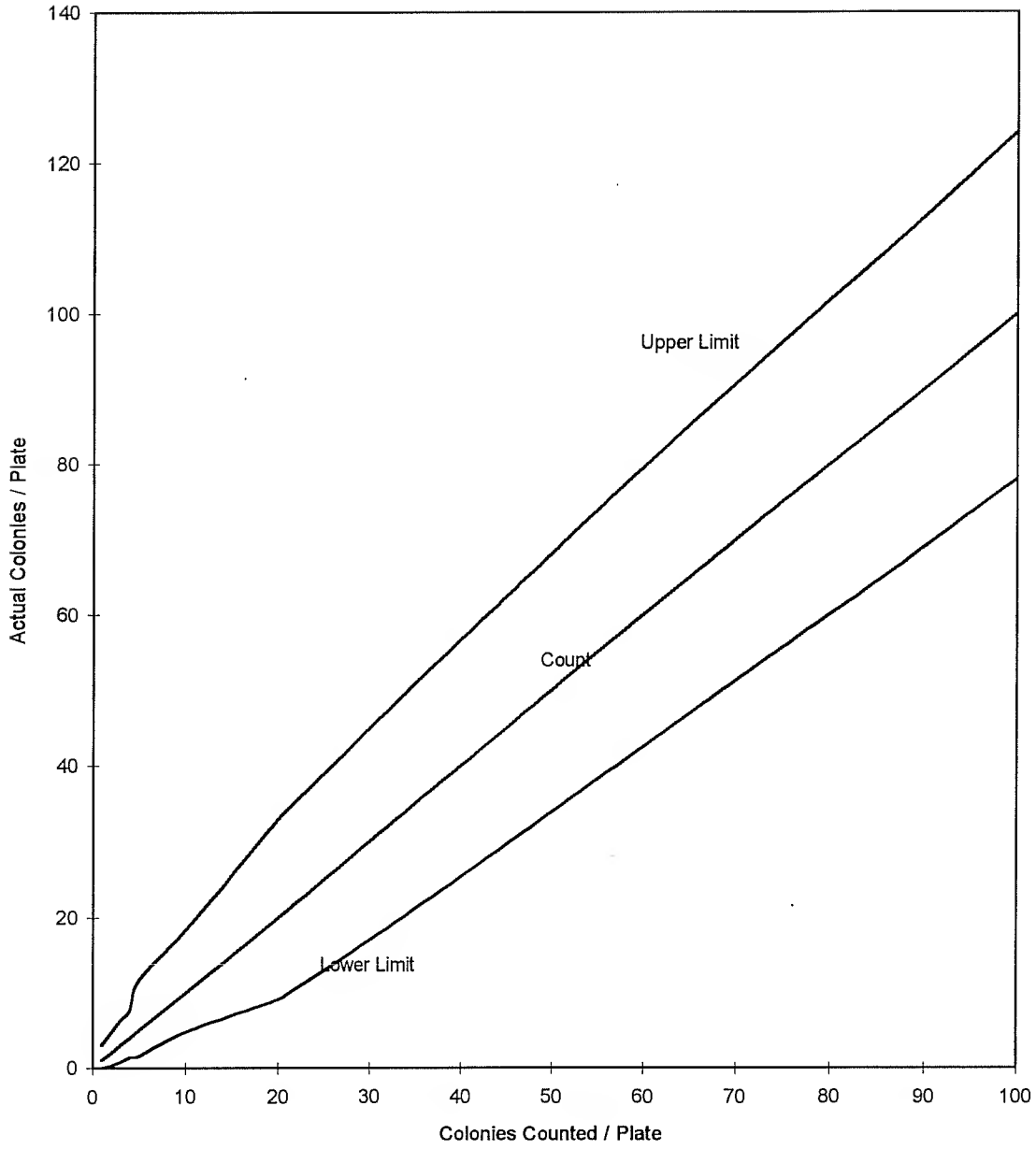

Figure 3.1 95% Confidence Limits For Membrane Filter Technique / Faecal Colifoms

aggregated or associated with some larger particle often straining and sedimentation will produce a marked reduction in bacterial concentrations.

Many bacteria secrete a slimy material, or capsule (Brock and Madigan 1991). Its function is to protect the cell and help it to attach to surfaces. Generally the overall surface charge of bacteria is negative so bacteria will be electrostaticly repelled from freshly crushed quartz sand. Most bacteria are harmless to humans but many will establish an infection when they are consumed. Often it will take several million organisms to cause a sickness.

Cholera is a serious and widely feared disease in the developing world. The bacteria *Vibrio Cholerae* is the microbe responsible for this disease. This bacteria has many similarities to the *E. coli* bacteria in its shape size and how it lives. Cholera is an exclusively human disease, it will not infect other creatures, and is transmitted mainly through water and food. The low pH of the stomach is relatively effective in preventing cholera as 10^8 to 10^9 cells must be consumed before an infection can be established. The number of cells required is reduced if the cholera bacteria are protected from the low pH of the stomach by food.

3.4.2 *Viruses*

Viruses are the smallest disease causing agents. Viruses are responsible for many diseases transmitted by all pathways. Viruses transmitted by water usually cause nervous system disorders rather than diareha. Polio and Infectious Hepatitis are well known viral diseases which can be transmitted by water.

A virus is normally a piece of genetic code enclosed in a protein coat. Viruses are obligate parasites. This means to reproduce the virus must infect a host cell and use the cell's "machinery" to make more viruses. The genetic code of a virus contains the information to make new viruses but does not contain in itself the ability to reproduce. Viruses can range in size from 0.02 to 0.30 μm. Smallpox , a very large virus, is 0.20 μm in diameter while Polio is one of the smallest at 0.028 μm. Viruses are particularly nasty since as few as one active virus has the potential to cause a sickness. (Brock and Madigan, 1991)

Conventional water treatment methods rely on sweep coagulation to agglomerate virus particles and then settle or strain the flocs out. Removal of turbidity has a large effect on viruses since they are often attached or associated with particulates causing turbidity. Disinfection is effective against viruses and destroys them by oxidising the proteins and nucleic acids they are made of. Coagulation and

sedimentation remove 85 - 99.99% of viruses. Rapid sand filtration will remove 0-87% of T-2 coliphage (virus specific to coliform). This is the result mainly of removing viruses associated with turbidity. The performance of rapid sand filtration improves significantly with the addition of coagulation as a step prior to filtration. Slow sand filtration removes 95 - 100% of polio viruses and 99.75 -99.996% of NS2 coliphage, substantially better than rapid sand filtration. (Wheeler et al, 1988)

Viruses are removed in slow sand filtration by adsorption and inactivation. Although McConnel found no difference between clean and ripened sand (McConnel 1984) several researchers have concluded that virus removal is mainly a biological process (Wheeler et al. 1988). Adsorption of viruses to sand particles in slow sand filters is likely the result of the high cation exchange capacity of the zoogeal layer that develops around sand grains. Also the chemical composition of viral proteins causes them to be attracted by and attach to cell surfaces. Once the viruses are attached to the sand grains they are metabolised by cells or inactivated by antiviral chemicals, like stalon, produced by micro-organisms in the filter (Ellis 1985).

3.4.3 *Cysts and Water*

Another very common class of pathogens in water are cyst forming protozoa. The most common cause of dysentery in the United States is the result of cysts of

Giardia lamblia. *Giardia* is also know as beaver fever because it commonly infects beavers (Lin 1985). Other cysts forming pathogens like *Cryptosporidium* and *Entamoeba histolytica* also cause forms of dysentery. Cysts pose special problems since they are resistant to conventional disinfection and are difficult to destroy or inactivate. Many communities in North America using pristine mountain streams as a water source and practising only chlorination have been subject to outbreaks dysentery caused by cyst forming pathogens. The renewed interest in slow sand filtration in the United States during the 1980s was due to its ability to remove a very high proportion of cysts (> 99.99, Bellamy et al. 1985a). Cysts of *Cryptosporidium sp.* and *Entoameoba sp.* cause symptoms similar to *Giardia.*

Much research has been done on *Giardia* during the 1980s and other cysts forming pathogens have very similar characteristics. The cysts enter the water through the faeces of infected people or animals. Cysts of *Giardia* and *Entoameoba* are 7 - 12 μm in size, while cysts of *Cryptosporidium* are smaller. These cysts are highly resistant to chlorine and concentrations of more than 5 mg/l free residual chlorine, more than 10 times normal residuals, are required to destroy them effectively. Cysts are also resistant to iodine, ozone and ultraviolet radiation. Cysts of *Giardia* can be carried by any mammal and domestic dogs are thought to be a continual source of this pathogen. Once in a stream, the cysts of *Giardia* can remain viable for up to 2

months and cysts of other pathogens are similarly robust. Cysts are also very virulent and three or four cysts can cause the disease. (Lin 1985)

Conventional rapid sand filtration (RSF) is capable of removing 99.99% of these cysts provided that proper coagulation is practised (Lin 1985). It has however been demonstrated that turbidity is connected to cyst removals in RSF. A small variation in turbidity will result in a large fluctuation in cyst concentrations (AWWA 1985). This means that at the end of a run, when a turbidity break through occurs RSF will remove only 20-60% of cysts.

Under normal circumstances conventional water treatment is not continuously effective in removing cysts. If RSF breakthrough occurs disinfection will not deactivate the cysts. Those communities using disinfection alone never provide a barrier to encysted pathogens.

4.0 DEVELOPMENT OF INTERMITTENT SLOW SAND FILTRATION

The first wealth is health.

- Ralph Waldo Emerson

The story of intermittently operated slow sand filters begins with the first slow sand filters built in the early part of the 19th century. These first filters are the basis of all sand filtration technology used today and provide an important background supporting this research. The need for an intermittently operated filter was observed by many but, a successful adaptation of the continuous slow sand scale filter process was not made until Dave Manz developed his hypothesis in 1991.

The basic design and operation of slow sand filters has not changed significantly from the one James Simpson designed and built in 1829 for the Chelsea Water Co., London (Scott 1955). A slow sand filter is basically a container filled with sand, having an underdrain systems to withdraw the water from the bottom and a means of adding water to the top of the filter. The flow rate of water through the sand is controlled by controlling the depth of water above the sand (the supernatant) or adjusting valves at the outlet while keeping the supernatant level constant with overflows. The removal efficiency of slow sand filters is partly due to characteristics of the sand but is mainly the result of micro-organisms colonising the filter material.

These micro-organisms are concentrated in a layer of detritus at the sand water interface and in the top few centimetres of sand. The layer of detritus and particles at the sand water interface is known as the schmutzdecke or filter skin and is often used interchangeably with the term biological layer although the biological layer extends 20 - 30 cm into the sand (ASCE 1991). The biological layer is responsible for the high removal efficiency of slow sand filtration.

For nearly as long as there have been people, methods for improving the quality of water have been used. Until recently these methods have mainly been used to improve the aesthetic quality of water, that is clarity, colour and odour. With the development of the germ theory of disease in the mid 19th century, the health aspects of water became a much greater concern (Brock and Madigan 1991). The use of sand for filtration on a large scale is well known and many attempts to reduce the benefits of slow sand filtration to a household scale are documented. Unfortunately the characteristics of slow sand filtration which make it effective were not preserved in the smaller scale versions. This along with problems with implementation, impractical design and cultural acceptance, have prevented the large scale acceptance of household filters of any type (Manz and Buzunis 1995).

Initial testing of an intermittently operated slow sand filter designed to protect the sand bed from disturbance and to control the water level during paused periods to a

shallow depth have produced results as good as results expected from full scale continuous slow sand filters. These tests along with several field tests have supported the initial hypothesis, that the biological layer can be maintained during paused periods, and demonstrate that more investigation is required.

4.1 History of Filtration

The first identifiable slow sand filter (SSF) was constructed in 1804 by John Gibb to supply clear water to his bleachery. He sold the excess water to the inhabitants of Paisley, Scotland. Filtration for domestic supply began in 1829 when James Simpson constructed filters for the Chesla Water Co. that supplied parts of London. (Scott 1955). This filter was the first of its kind and laid the foundation of slow sand filtration practice today (AWWA 1991). Out of these first large scale filters evolved present forms of granular media based filtration. Slow sand, rapid sand, and intermittent filtration (waste water treatment) all developed from these beginnings.

The first filters were used primarily to remove turbidity. It was observed that a layer of detritus material, mud and slime formed at the sand-water interface. This layer was removed by scraping when the filtration rate became too slow. The layer of mud and slime was called the schmutzdecke, German for dirt blanket. It was not until 1855 when John Snow proved disease could be transmitted by contaminated

water (Brock and Madigan 1991) that filtration was discovered to remove the agents of disease. It was thought that cholera patients emitted an infectious agent in their faeces that could be strained out by SSF. In 1876 Robert Koch developed the Germ Theory of Disease, proving that micro-organisms cause sickness (Brock et al. 1991) and in 1886 Koch's bacteriological techniques were used to demonstrate that SSF removed bacteria (Scott 1955). At this time, the schmutzdecke was found to be composed mainly of microbes and the importance of the biological removal mechanisms realised (Hazen 1907).

4.2 The Continuous Slow Sand Filter Process

The community of micro-organisms is carried into the filter with the raw water. These micro-organisms colonise the filter and live off the food and dissolved oxygen also supplied by the influent. A diversity of life develops in the filters consisting of algae, bacteria, protozoa, and small invertebrates. The micro-organisms and the relative number of each species are specifically adapted to the characteristics of the influent water source and the environment of the filter. The biological processes of removal are the result of poorly understood natural interactions between the micro-organisms living in the filter (AWWA 1991).

Beginning with clean sand, the filter initially removes contamination using only physical mechanisms like straining and sedimentation. It takes time for the biological factors and micro-organisms to colonise and grow to an extent where there effects can be noted. The initial ripening time of the filter starting with clean sand may be from 1 to 3 weeks (Huisman and Wood 1974, Visscher et al. 1987). The ripening process depends on many factors but mainly raw water composition and temperature. With water containing a high organic loading there is abundant substrate for micro-biological growth allowing a population to develop quickly. Temperature is an important factor since it controls the rate at which the microbes can grow and metabolise substrate. A 10 °C increase in temperature will approximately double the respiration rate of most microbes and decreasing ripening time (Curry 1992).

Organic material is broken down into nitrate compounds, carbon dioxide and water as it passes through the filter and is metabolised. The micro-organisms in the filter use the organics for growth and energy. Micro-organisms near the surface of the sand partially break substances down and then pass simpler organic compounds down to other microbes living deeper in the filter. As the organic material passes through the filter less and less is usable for energy and growth. After about 40 cm, in filters described by Huisman and Wood, there is very little organic material left in the water for microbes to survive on. Microbes that reach this depth starve.

Generally, micro-organisms in slow sand filters are closely associated with the sand particles and will tend to survive only in the upper sand layers and supernatant where food is abundant (Huisman and Wood 1974).

Algae has been a significant problem in slow sand filters. Algae blooms in filters are never desirable since they contribute to rapid clogging of the filter and increase the frequency of cleaning. For this reason COSS filters are often covered with a roof. The algae find the supernatant of the SSF a very good place to grow. Provided with fairly stagnant water the algae population can multiply readily. This creates problems for the COSS filtration process. Since it is an aerobic process it needs a minimum dissolved oxygen content and the diurnal variation of oxygen resulting from large algae growths may cause the filter to become anaerobic during the night and produce obnoxious tastes, smells and colour as well as a decline in bacteriological quality (Huisman and Wood 1974).

4.3 The Efficiency of Continuous Slow Sand Filtration

Early on it was shown that SSF was effective in removing disease from water. A cholera epidemic in Hamburg in 1892 killed 13.39/1000 while in the neighbouring city of Altona there were only 2.09 deaths/1000. Hamburg delivered untreated water while Altona drew its water downstream from Hamburg but treated it with SSF. The

lower number of deaths in Altona were attributed to migration and other sources of infection other than the water supply. (Hazen 1907).

Hazen states "It may be said that filtration as now practised in Europe never allows over 1 or 2 per cent of the bacteria of the raw water to pass, and ordinarily not over one forth to one half of one per cent, . . . " This quote shows the effectiveness of SSF even though at the time microbiology and the germ theory of disease were less than 30 years old. Since then many authors and studies have confirmed the ability of the SSF process to remove a large proportion of bacteria. Researchers generally report 99-100% removals of total and faecal coliform under normal operating conditions Reported removals are influenced by many variables and low temperatures have often caused removals lower than 99%. It is only on the rarest occasions with unusual conditions that the bacterial removal efficiency falls below 90%. (Bellamy et al. 1985a, Bellamy et al. 1985b, Burman 1962, Burman and Lewin 1961, Cleasby et al. 1984a, Cleasby et al. 1984b, Ellis 1985, Foreman 1985, Fox et al. 1984, Hazen 1907, AWWA 1991, Huisman et al. 1974, IRC 1987, Joshi et al. 1982, Joshi et al. 1985, Logsdon and Lippy 1982, McConnel 1984, Paramasavam et al. 1980, Schuler and Ghosh 1991, Visscher et al. 1987, Williams 1987).

Studies have also been conducted to determine the removal efficiency of SSF for viruses. The removal of viruses normally exceeds faecal coliform removals.

Depending on the actual characteristics of the SSF virus removals have been reported in the range 99.9-100%. (ASCE 1991, McConnel 1984, Visscher et al. 1987, Wheeler et al. 1988).

During the 1980s there was a renewed interest in SSF due to the need to remove cysts of *Giardia* and *Cryptosporidium* from water. The removals of these are reported in two studies as >99,99% to 100% removal of *Giardia* and 99.99% removal of *Cryptosporidium*. (Bellamy et al. 1985a, Schuler and Ghosh 1991). Removal of these cysts by filtration is extremely important due to their extreme resistance to disinfection.

Although no studies were found to show the ability of the SSF process to remove schistosome cercariae, the cause of schistosomiasis, a study of the removal efficiency of clean sand columns showed 100% removal in a 92.5cm sand column (Bernarde and Johnson 1971). The biological action of SSF will certainly improve this. Additionally, Vischer et al. (1987) say of the performance of SSF "virtual removal of cercariae of schistosoma, cysts and ova" is acheived though no reference is given.

4.4 Design and Construction

One of the main components of a slow sand filter is a container. This could be a concrete box or a lined dugout. The container is first fitted with an underdrain usually covered by several layers of carefully graded gravel. The gravel supports the sand bed. An area is provided above the sand bed to provide a head for gravity flow through the filter and to keep the sand from being scoured by the inflow of water. A sketch of a COSS filter is included in Figure 1.1. In addition to the basic filter, inlet structures, scum removal structures, drains, valves and weirs are provided to facilitate filter operation.

4.4.1 *Containers*

Any container that is water tight may be used for slow sand filtration as long as it has the required depth to accommodate the supernatant, sand bed and underdrain. The depth of the containers for a COSS filter is normally 3.0 - 4.5 m. The container must be water tight to prevent surface runoff and shallow ground water from contaminating the filtered water (Visscher et al. 1987). The surface area of the filter must be adjusted along with the rate of filtration to produced the desired quantities of treated water.

The size of a slow sand filter is based on three criteria. First it is suggested by Huisman and Wood 1974 that filters less than 10 m^2 in surface area should not be used because short circuiting along the sides of the container becomes significant. However, AWWA 1991 has shown that as long as the container surfaces have been properly roughened, short circuiting does not occur. The second criteria is an upper limit controlled by the time it takes to scrape the sand surface during cleaning. The surface area of a single filter unit should not exceed what can easily be scraped in a single day. Values suggested for this are around 200 m^2 (AWWA 1991). The reason for this is to reduce the time over which additional loading is applied to other filtration units in the plant. A minimum of two filter units should always be constructed to allow one to be cleaned while the plant still provides water.

The third criteria used to size the filtration area is water demand. The area of the filter multiplied by the loading rate over 24 hrs. should exceed the demands of the community being served by the filter. Because it is a continual process and water use even in large communities fluctuates with time, storage is required as a separate structure. (Vischer et al. 1987)

4.4.2 *Inlet*

The purpose of the inlet structure is to add water to the filter without disturbing the sand surface and schmutzdecke. Many, different systems to accomplish this are

used. Most commonly a plate is used to keep the jet from the inlet pipe from scouring the sand. Also deep boxes as well as weirs have been used. These boxes also have a drain to allow the supernatant to be drained for filter cleaning (Visscher et al. 1987)

4.4.3 *Supernatant*

The supernatant water layer provides the head that causes flow through the sand bed. In COSSF this layer of water is normally between 0.75 - 1.50 m. This layer also causes a retention time of several hours which allows natural die off and predatory microbes to remove some pathogens. Most often rate is controlled by adjusting a valve at the outlet and the supernatant is kept at a constant depth sometimes however the rate of filtration is controlled by gradually increasing the supernatant depth as headloss through the filter increases.(Visscher et al. 1987).

4.4.4 *Sandbed*

Although any inert durable granular media of the correct effective size and uniformity coefficient can be used, sand is readily available in many environments. Effective size is defined as the size of the sieve openings that allows 10% of a sample of granular media to pass by weight. Many times effective size is denoted as d_{10}. The

uniformity coefficient is another term used to specify granular media characteristics. It is calculated as the d_{60}/d_{10}, where d_{60} is the size of the sieve openings that allows 60% of granular media to pass by weight (Hazen 1907).

Media should be hard durable grains, slightly rounded, as from a river bed, and free from clay, soil and organic matter. It may be necessary to wash these constituents out of the sand. Also if the raw water is expected to have high concentrations of carbon dioxide, less than 2% calcium and magnesium should be allowed. This is to prevent the formation of voids in the media if the calcium and magnesium are removed by solution (Huisman and Wood 1974).

Effective sand sizes between 0.15 and 0.35 mm have been used almost uniformly throughout existing COSSF practice. However, both finer and coarser sand have provided satisfactory results (Barrett 1989). Sand size is chosen based on whether clogging occurs frequently, causing more than one cleaning each month and whether the filtered material penetrates too deeply into the sand bed. More the 0.5 to 2 cm, or what will be removed by a single filter scraping will eventually clog the filter at depth requiring the replacement of all the sand in the bed. As sand sizes increases it is often necessary to increase sand bed depth in order to offset the loss of surface area in the material. Only a limited amount of contamination is removed by straining in slow sand filters. Sedimentation and surface interactions between

contaminants and sand grains are much more important. For example at the smallest sand size commonly used, 0.15 mm, the pore openings are about 0.02 mm which is over ten times the size of common bacteria while much more than 1000 m^2 is available for sedimentation (Huisman and Wood 1974). Increasing the sand size will severely reduce the surface area in the filter.

If surface interactions were primarily responsible for removals it would be expected that doubling of the effective sand size would require, roughly, a doubling of the sand bed depth for similar removals to be achieved. However, because of the biological nature of COSS filtration this is not true. The depth to which the biologically active layer penetrates is a function of sand size, flow rate and raw water quality. Removal efficiency is mainly a function of contact time and loading rates applied to the bio-films growing on the sand grains. Increasing the sand bed depth will not alter the characteristics of the biological layer if the biologically active layer does not exist through the entire sand bed depth, however reducing the sand size and thus increasing the surface area available for bio-film growth will increase the contact time and effectiveness of a filter.

Huisman and Wood (1974) suggest that the biological layer is 0.3 to 0.4 m deep, and deeper biological layers correspond to higher flow rates and coarser sand. Huisman and Wood 1974 describe another zone as well, about 0.5 m deep in which

chemical oxidation takes place and suggest an overall bed depth of 0.9 to 1 m which includes enough so that several cleaning could occur without resanding. Visscher et al. 1985 propose a sand bed depth a minimum of 0.5 m with about 0.1 m added to allow for several cleaning. ASCE 1991 show that the majority of the biological processes occur in the top 0.4 m of the sand bed and support the proposed minimum depth of 0.5 or 0.6 m with an initial depth of 0.9m to allow many filter scrapings before resanding is needed.

The uniformity coefficient is another parameter used to characterize sand. Uniformity coefficient is defined as the d_{60} size (size of sieve allowing 60% of the sample by weight to pass) divided by the d_{10} or effective size. A uniformity coefficient (UC) of less than 3 is suggested by Huisman and Wood (1974) with a coefficient of 2 being preferred. Visscher et al. (1987) suggest similar UC ranges but will accept a UC of less than 5 with less than 3 preferred. This parameter controls two things within the sand, the size of the pore openings and the surface area of the sand. This controls both the depth to which detritus material will penetrate the sand surface, affecting the depth that must be scraped, and the removal efficiency.

4.4.5 *Filtration Rate*

Recommended filtration rates for slow sand filters are 0.05 $m^3/m^2/hr$ to 0.40 $m^3/m^2/hr$ with the 0.40 $m^3/m^2/hr$ rate acceptable for short periods only. The standard rate used is 0.20 $m^3/m^2/hr$ and was used on the first filters. Research by Bellamy et al. 1985a showed that over a range of between 0.04 $m^3/m^2/hr$ and 0.40 $m^3/m^2/hr$, coliforms and *Giardia* removals were consistently high. That is greater than 98% for coliforms and greater than 99.9% for *Giardia* at the highest loading rate. On some slow sand filters, used with pre-treatment by rapid sand filters or micro-straining, rates as high as 0.5 $m^3/m^2/hr$ have been used successfully (Ellis 1985).

Slower filtration rates are preferred since generally they provide water of better quality. This is the result of two interactions. First a slower filtration rate provides a longer contact time which allows the biological processes to remove a larger proportion of the contamination. Second, slower rates place less shear on the bio-films growing on the sand grains. This allows thicker bio-film growth which means there are more micro-organisms living in the sand bed. This larger population has a larger demand for food and will absorb more contaminants from the water being filtered. There is a limit to how slow the filtration rate can be however. The slow sand filtration process is aerobic (Ellis 1987, Visscher et al. 1987). The biology existing in the filter requires a minimum of 3 mg/l dissolved oxygen at normal flow

rates (Ellis 1987). As the water passes through, oxygen is used by the micro-organisms in the filter as they respire. If the flow rate becomes too low the oxygen in the water is used up and the processes become anaerobic causing undesirable tastes and odours as well as a decline in bacteriological quality (Paramasivam et al. 1980).

The general consensus among slow sand filtration experts is that flow rate variations in COSS filtration is undesirable. Flow should be kept as constant as possible and Intermittent operation, stopping the flow of water through the filter, should never occur. Vischer et al. 1987 felt strongly enough to place the following statement in bold print: "intermittent operation should not be permitted". This caution resulted from experiments where a serious decline in bacteriological quality occurred in filters 4 to 5 hours after the filter had been started again (Visscher et al. 1987). The original research done on intermittent operation of full scale filters showed that the decline in bacteriological quality coincided with a decline in dissolved oxygen levels and the worst water quality coincided with the water that was most closely associated with the biological layer during the stoppage of filtration (Paramasivam et al. 1980).

4.5 Previous Household Filter Designs

From ancient times people have attempted to improve the quality of their water. Using a fabric to strain out course particles, porous pots to filter and cool water, and skimming off surface debris are just a few of the methods that have been used. Until recently this was usually an attempt to improve the aesthetic quality of water and any improvement in the health aspects of water was coincidental. With the discovery of the germ theory of disease and the connection of water to the transmission of the major diseases of the 19th century, typhoid and cholera, the safety of water became the primary focus. In particular the problem of rural areas in developing countries has resulted in the several versions of the household sand filter. Generally, these filters are operated intermittently that is water is only run through the filter when needed.

4.5.1 *WHO, Household Water Filter*

The World Health Organisation describes a household size water filter made from a 45 gallon drum. A reproduction of the WHO Water Filter drawing is given in Figure 4.1. The drawing and accompanying description suggested that a water layer as deep as possible, in the order of 40 cm, be preserved over the sand bed. The use of large flat stones covering the sand surface prevents sand disturbance. This layer

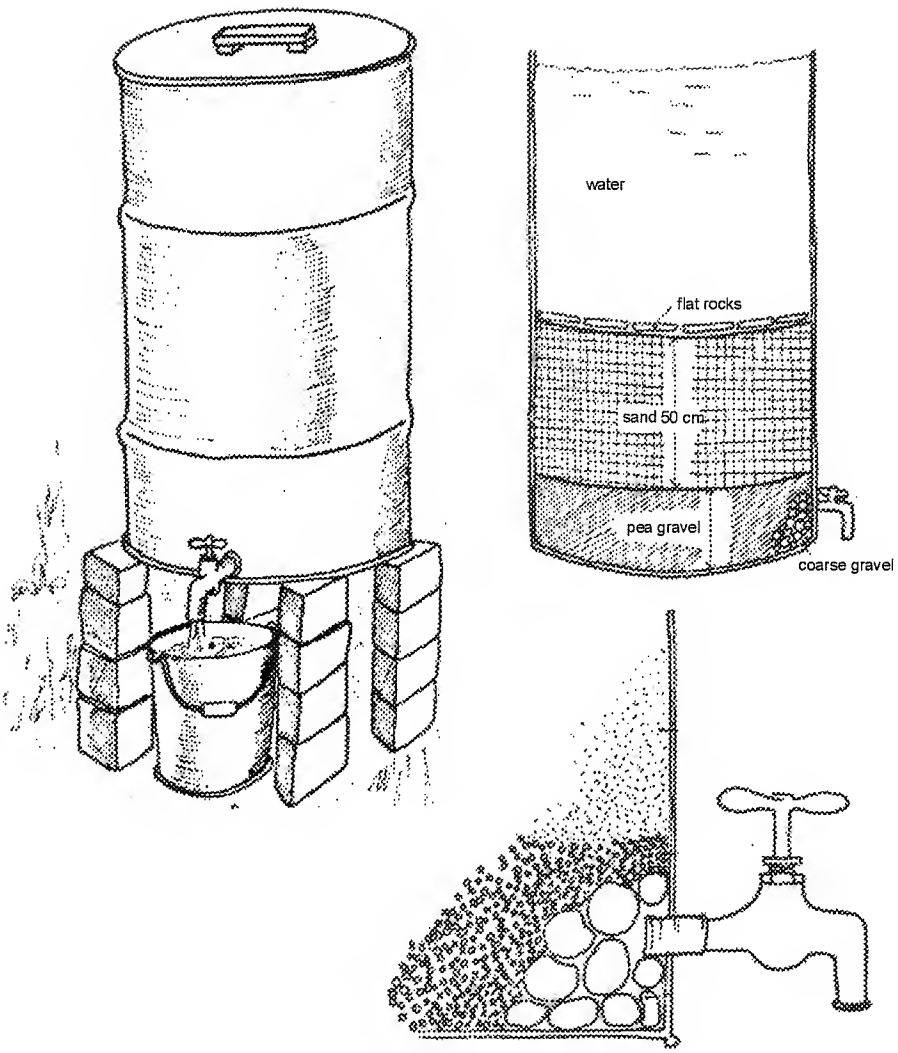

Figure 4.1 Household Water Filter (from WHO 1987)

of flat stones will also prevent the formation of an abundant biological layer and increases the pore velocity of water travelling between them. The location of the valve outlet will not prevent the sand from being dewatered if it begins to leak or is accidentally left open. The performance of sand filters in general is described as removing some germs and the eggs of some worms making the water "less dangerous" (WHO 1987). It is certain that this filter will, after time, improve the clarity of the water but the removal of pathogens is questionable. Although no reference is given, the description of construction, operation and maintenance of this filter is based on the standards for continuous slow sand filters. Unfortunately, the book from which this design comes is completely unreferenced and no information on actual field installations or measured performance could be located.

4.5.2 *Blair Research Laboratory, Family Sand Filter*

At the Blair Research Laboratory in Zimbabwe, Peter Morgan developed a filter very similar to that suggested by the WHO. The two significant differences being the use of one large flat stone in the centre of the sand surface used to prevent sand disturbance and the use of a riser pipe which allows the valve to be located slightly above the sand surface and prevents the dewatering of the sand bed if the valve is left open or begins to leak. (Morgan 1982) Again no actual references are given but

the recommendations in the text are virtually identical to those found in standard texts for full scale continuous slow sand filters.

4.5.3 *The Myriad of Household Water Filters*

In addition to the previous two household filters, which appear very similar to the one tested in this research, there have been many other attempts to build an effective, cheap and robust household filter. Several are simply small continuous slow sand filters with either an elevated influent tank (Vigneswaran et al. 1983), or connected to a pressurised system (VITA 1988) allowing continuous flow. Others use alternative filtration media like activated carbon (Ogedengbe 1984, IDRC 1981), clay wicks (Kirkpatrick 1943) or silver impregnated wicks (Wagner and Lanoix 1959). Still others are, like the previous two detailed examples, the continuous filter design reduced to small scale and operated intermittently (IDRC 1981, Winston 1945). Additionally, there are the traditional methods like porous stone (Hazen 1907) or porous clay pots typical of northern Honduras near Santa Rosa Copan.

None of these household filtration systems have gained wide acceptance. The main causes of the lack of acceptance falls under two categories, poor design and lack of cultural acceptance. Poor design includes ineffective, expensive or impractical designs that either are complex to operate, have components that will break or wear

out or do not account for the creativity of users in modifying the filter in ways which cancel the health benefits (Manz and Buzunis 1995). A lack of cultural acceptance has as much to do with implementation as with cultural aspects. A project improperly implemented, without proper community education and follow up as well as lacking a proven effective design is sure to fail (Manz and Buzunis 1995).

4.6 Development of Intermittently Operated Slow Sand Filters

The original hypothesis that allowed successful adaptation of the slow sand filtration process to intermittent small scale household operation resulted from international development work Dr. David Manz had done in South Africa and the Philippines. At this time the hypothesis developed that maintaining the schmutzdecke undisturbed wet and aerobic would produce similar results as in continuously operated slow sand filters. This meant that a shallow water layer must be maintained above the sand bed to allow oxygen to diffuse to the sand bed and some way of preventing the sand from being disturbed when water was added had to be developed (Manz 1991). The intermittently operated slow sand filter is basically a container filled with sand. After many design improvements and modifications it now includes a diffuser plate and a overflow water level control on the outlet. A drawing of the current design is included in Figure 4.2.

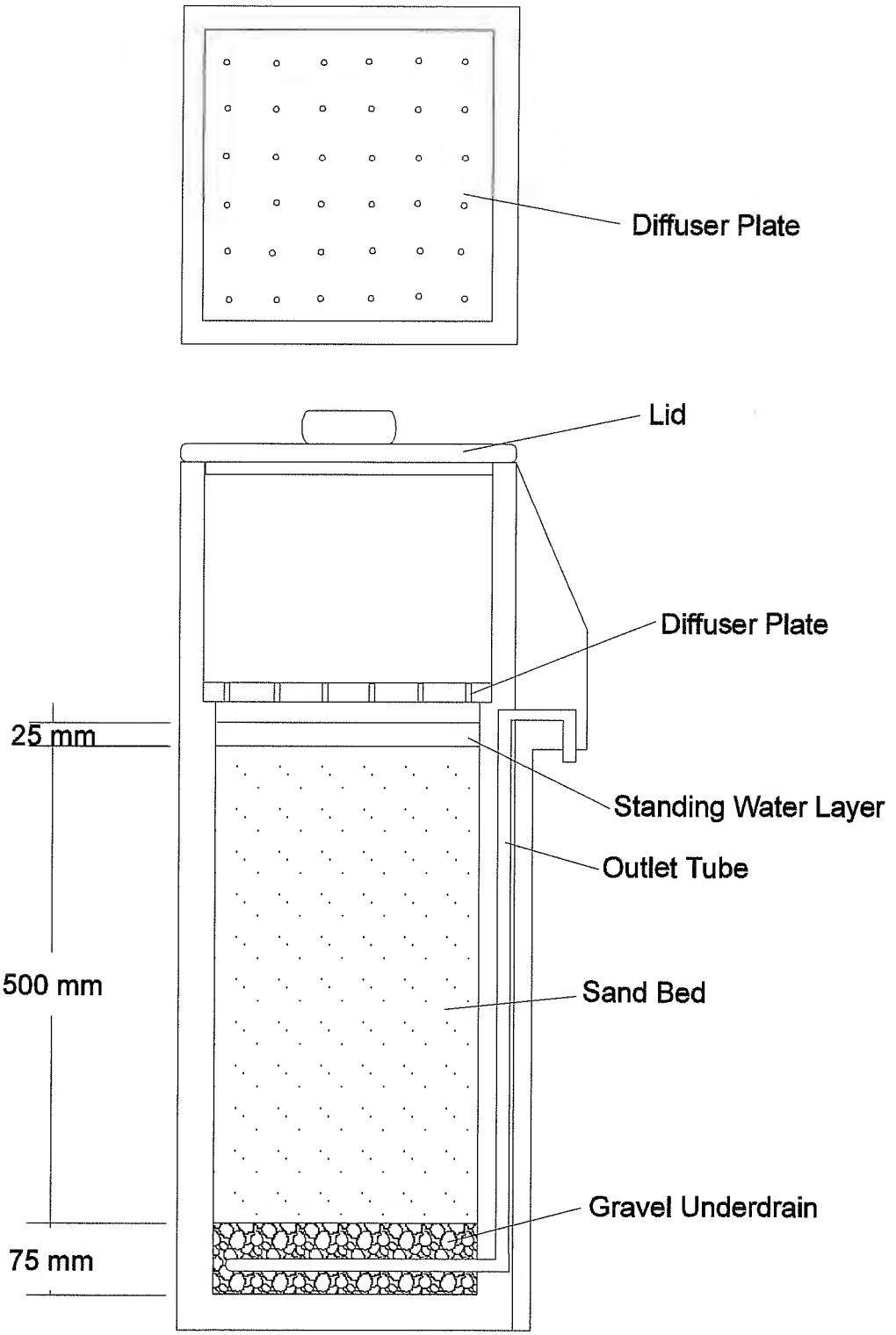

Figure 4.2 Sketch of Concrete Filters Used in Nicaraugua

4.6.1 *The First Try: Garbage Can Filter*

The first proven effective intermittently operated slow sand (IOSS) filter was constructed by David Lee for an undergraduate project course supervised by Dr. Manz near the end of 1991. The first filter used a plastic garbage pail for the container and had a sand bed of approximately 40 cm depth and used a declining loading rate, starting at approximately 0.7 $m^3/m^2/hr$. The filter used the garbage pail lid inverted and with holes drilled in it to prevent the sand from being disturbed. Although not specifically controlled the water level was maintained between 5 and 15 cm above the sand surface. This first filter removed 99.8% of total coliform indicator organisms (Lee 1991). A short summary of the data from this preliminary study is included in Appendix A.

4.6.2 *PVC Pipe Filter*

After an extensive literature review, conformational tests of a second IOSS filter were began. This second filter was constructed from a length of 15 cm diameter PVC pipe, contained a sand bed 50 cm in depth and operated with an average flow rate of 0.4 $m^3/m^2/hr$. A special funnel was used to prevent sand disturbance when water was added. The water depth over the sand bed was controlled to 2.5 cm above the sand bed. This filter confirmed the results found in the previous study.

More than 98.89% of faecal coliform indicators were consistently removed (Buzunis 1993). The laboratory report describing this test is included in Appendix B.

4.6.3 *Nicaragua Pilot Project*

The proven design resulted in a pilot project taking place in the rural areas around the town of Nandaime, Nicaragua, Central America. The project was accomplished through the Division of International Development at the University of Calgary and with funding from the Pan American Health Organisation. Four intermittently operated slow sand filters were built and established in three rural households and a hospital using the proven design. These filters removed more than 99.1% of the faecal coliform indicator organisms as tested by the Project Laboratory established at the Health Centre in Nandaime and confirmed by the Ministry of Water and Sanitation Laboratory. This number is very conservative since an actual concentration of indicator organisms in the influent water could not be determined. It is estimated that the concentration of indicators in the influent was about 10 000 colonies/100ml but the method used to measure simply termed this concentration much greater than 2000 colonies/100ml. For this reason the low value of 2000 organism/100ml was used to calculate the removal rate (Manz et al. 1993).

4.6.4 *A Concrete Filter*

Another filter was constructed from concrete by technologists Terry Nail, and Harry Polard and designed by David Manz, in an attempt to make them more suitable for application in Nicaragua. Manufacture of wash basins and building blocks from concrete is a wide spread indigenous skill in Nicaragua. This filter had a 20 cm sand bed and a 5 cm water layer. The influent water used to test this filter had very low concentrations of faecal coliforms, usually less than 10 organisms/100ml. After two weeks of operation, when the filter developed a biological layer, removals of faecal coliform indicator organisms continually were 100% (Buzunis 1993). The Table and a summary of this short investigation is included in Appendix C.

4.6.5 *Laboratory Filters*

Another experiment tested three slow sand filters with varied standing water depths of 5, 30 and 60 cm. As well, a continuously operated filter was operated in parallel. For this experiment an attempt was made to produce a consistent level of contamination in the influent water. This was done by incubating raw hamburger diluted in dechlorinated tap water in a bath at 37 °C. This produced a high concentration of faecal coliform indicators however it was not stable. Concentrations ranged from 10^5 to 10^8 faecal coliforms/100ml. A small amount of

this spike was added to the influent once or twice a week in an attempt to limit the variation of contamination. However the 24 hour lag time between faecal coliform sampling and results prevented immediate and exact reaction to influent variations. In addition the limited volume of the influent which was recycled caused the filters to significantly effect the reduction of bacteria in the influent tank with time. Faecal coliform removal data for these experiments was inconclusive. This was due to uncontrolled variations in the faecal coliform concentration of the influent as well as reasons discovered in subsequent experiments. This experiment, however, identified many of the problems associated with simulating a contaminated water source, and refined data colection protocols. In additon, a significant amount of detailed hydraulic conductivity data was found. The laboratory report describing this experiment is included in appendix D. (Buzunis 1994)

4.6.6 *Community Scale Project: Valle Menier, Nicaragua*

As a result of the positive results obtained from the pilot project in Nicaragua, funding was obtained from Health Canada to pilot the filters in Honduras and for a second phase community scale project in Nicaragua. The second phase involved installing filters in each household of an entire community. The project community Valle Menier was located about 4 km south of Nandaime and had a population of 326 in 56 households. The community was served by over 15 water sources

including wells, infiltration galleries, rivers and springs. Although many tests were inconclusive as a result of non-indicator bacteria preventing accurate counts, average removals of faecal coliform bacteria after 3 weeks of operation ranged from 86.67% to 100% and the average removal rate of all properly operated filters was 97.00%. Even though there was limited control over the operations and water sources used by the different households, the results again indicated the hypothesis is correct. (Manz and Buzunis 1995) Extensive excerpts from this report are included in Appendix E.

4.6.7 *Pilot Project in Honduras*

The pilot project performed in Nicaragua was repeated in Honduras using an improved design built from plastic containers and the overflow type water level control. The sites chosen for the Honduras project had well constructed and protected wells and so the contamination of the water in these situations was relatively low. In fact the contamination was so low in many cases to limit the accuracy of the testing. In cases were higher influent contamination was recorded removal rates were near 100% (Manz and Buzunis 1995).

4.6.8 *Continuation of Research*

Up to this point research of the intermittently operated slow sand filter has concentrated in two areas. First, to prove that the process is effective when operated in a fashion typical of what is expected in developing countries and second to introduce effective designs to rural users in the field and to adapt these designs to the cultural demands of the users. Because, the preliminary investigations were based on very little preliminary knowledge of both the process and of testing procedures only a limited amount of conclusive data could be obtained.

The laboratory testing of the filters began with the undergraduate project of David Lee before the hypothesis of shallow water levels and undisturbed sand had completely developed. This experiment demonstrated the robustness of the process since many of the important parameters including the volume of water run before sampling, water level maintained over the sand bed and influent water composition varied greatly and were not recorded. In addition, the effects of certain testing protocols like spiking influent water only on test days were not determined due to a low frequency of testing. The second laboratory test of the PVC pipe filter, more closely controlling the physical characteristics of the filter and standardising the sample point still did not produce much more than the general result that the filter performed effectively. This was on account of the time taken to gain enough

experience to perform micro-biological tests accurately and again can be linked to the difficulty simulating or obtaining a natural water source with fairly consistent level of contamination. The three column test in parallel with the continuous filter did produce a significant amount of data but the micro-biological data is in question due to the uncontrolled fluctuations of the influent micro-biological contamination. This again is due to problems with simulating a natural water source with a consistent level of contamination.

At first the problem of obtaining a natural water source with a stable level of contamination may seem like a relatively simple problem. Since, testing of water treatment processes has been going on for at least 100 years, it would seem a standard method for producing contaminated water must exist. In fact it does not. In addition, the method of introducing a "spike" of contamination will often effect the results of the process. The typical water treatment testing scenarios include using a natural source and then introducing a large spike of indicators into the influent (Bellamy et al. 1985a). A biological process not acclimatised to a high concentration of these indicators may be overloaded and the results obtained could show poorer results, where as a physical process may actually act in the opposite way and give better short term results. It is known that for slow sand filters the concentration of indicators in the influent affects the performance of the filter (AWWA 1991). Another typical way to test is to use a treated water source like city tap water that has been

dechlorinated as the main stock solution of water. Initially, for processes like slow sand filtration, the filter is inoculated with some biologically diverse water like water from a slough or back water (McConnel 1984) . Then several laboratory grown indicators are added to the influent during sampling periods. This will not provide accurate results for slow sand filters which depend highly on a diversity of biological life in the influent to establish and maintain an effective biological layer. Although many variations of the above two general protocols exist, the author is not aware of any that provide a natural diversity of micro-biological life with a stable concentration of indicator organisms.

Studies in the field, while important, are not of laboratory quality. Even when a qualified engineer was present to both perform and supervise testing, the variation in water supplies and the erratic use and unreported changing of water sources made interpretation of results difficult and all but very general results inconclusive. A majority of the time tests were not performed by experienced personnel but by minimally trained locals and thus the results are suspect. The additional problem of incomplete reporting of irregularities in filter use by the operators of the filters made all but the most general results suspect.

Although the filter is effective, little is known about how the operating characteristics affect the removal rates. The basic characteristics and the interactions between

different aspects in the filter are completely unexplored. Although, an extensive literature review was conducted and many household filter designs exist, research and testing of these types of small scale units could not be found in the literature. In fact the IOSS filter research and field household filtration project which the author has participated appears to be the only reported research of this type up to this time. The examination of the filters up to this point has been relatively uncontrolled and has only allowed the most general conclusions while supporting the original hypothesis. As a result of the conventional belief that variation in filtration rate results in failure of the continuously operated slow sand (COSS) filter process, it is certainly the first research on IOSS filtration.

Critical design parameters, more general effects on water quality, and interactions of different components must be investigated. Some ideas from continual slow sand filtration and rapid sand filtration may be useful for intermittently operated slow sand filters but these are not directly transferable. In order to design a safe, effective, and robust IOSS filter, a more detailed and controlled investigation must be conducted.

There are many potential applications of an intermittently operated slow sand filter. An intermittently operated slow sand filter could be used in any rural setting where distribution systems are not available. The filter is well suited for providing water for developing areas of the world because it can be produced cheaply, is easy to

operate, can be built from local materials, requires virtually no maintenance and is highly effective in removing pathogens. Modifications of the system would be well suited to small scale farm, cottage, and resort water supplies in the developed world as well.

5.0 INTERMITTENTLY OPERATED SLOW SAND FILTRATION

No theory is good except on condition

that one use it to go beyond.

- Andre Gide

5.1 Model

A novel approach to slow sand filtration is the realization that its major benefits are due to the microbiology of the filter. The microbiological community must be kept alive and if possible thriving for the filter to be effective. The biology in slow sand filters is aerobic and must be provided with sufficient oxygen (Manz 1991). In full scale filters sufficient, dissolved oxygen (DO) is provided by the continuous flow of raw water. In an intermittently operated filter, oxygen must be supplied in a different way during times when water is not flowing, during pause times. This is accomplished by diffusion and slow convective mixing of the supernatant. If the layer of water above the sand is kept small in depth, enough oxygen is able to pass through to the micro-organisms to keep them alive and thus effective.

The intermittently operated slow sand (IOSS) filter operates on similar concepts to continuous filters but has significant differences. The operational procedures that

allow intermittent operation to effectively remove pathogens effects how and where the micro-biological community lives within the filter. The way in which an IOSS filter works makes it a completely new process which has not been knowingly used before. Unlike intermittent sand filters used in waste water treatment which have a dose of contaminated water applied to the filter and then the filter is allowed to dry out, the sand bed in IOSS filters is kept wet. Tests previously done on continuous slow sand filters had a deep water level over the sand during the stopped period (Paramasivam et. al 1980) but the control of the water level in intermittently operated slow sand filters is critical to effective operation. Intermittently operated slow sand filters must have only a shallow water layer maintained over the sand bed during pause times.

Based on the previous testing described in Chapter 4 ideas developed which described the observations and gave inferences about what was occurring in the filter. Figure 5.1 is a cross-section showing the basic components of an IOSS filter. The filter is made up of five distinct regions, the influent reservoir, the supernatant, the schmutzdecke, the biologically active zone and the sand support and underdrain. The influent reservoir is the space provided for the influent water above the water held in the filter during pause times. This area only holds water during the time the filter is operating. The supernatant is the water held in the standing water layer over the pause time. There is always water here but during pause times it is

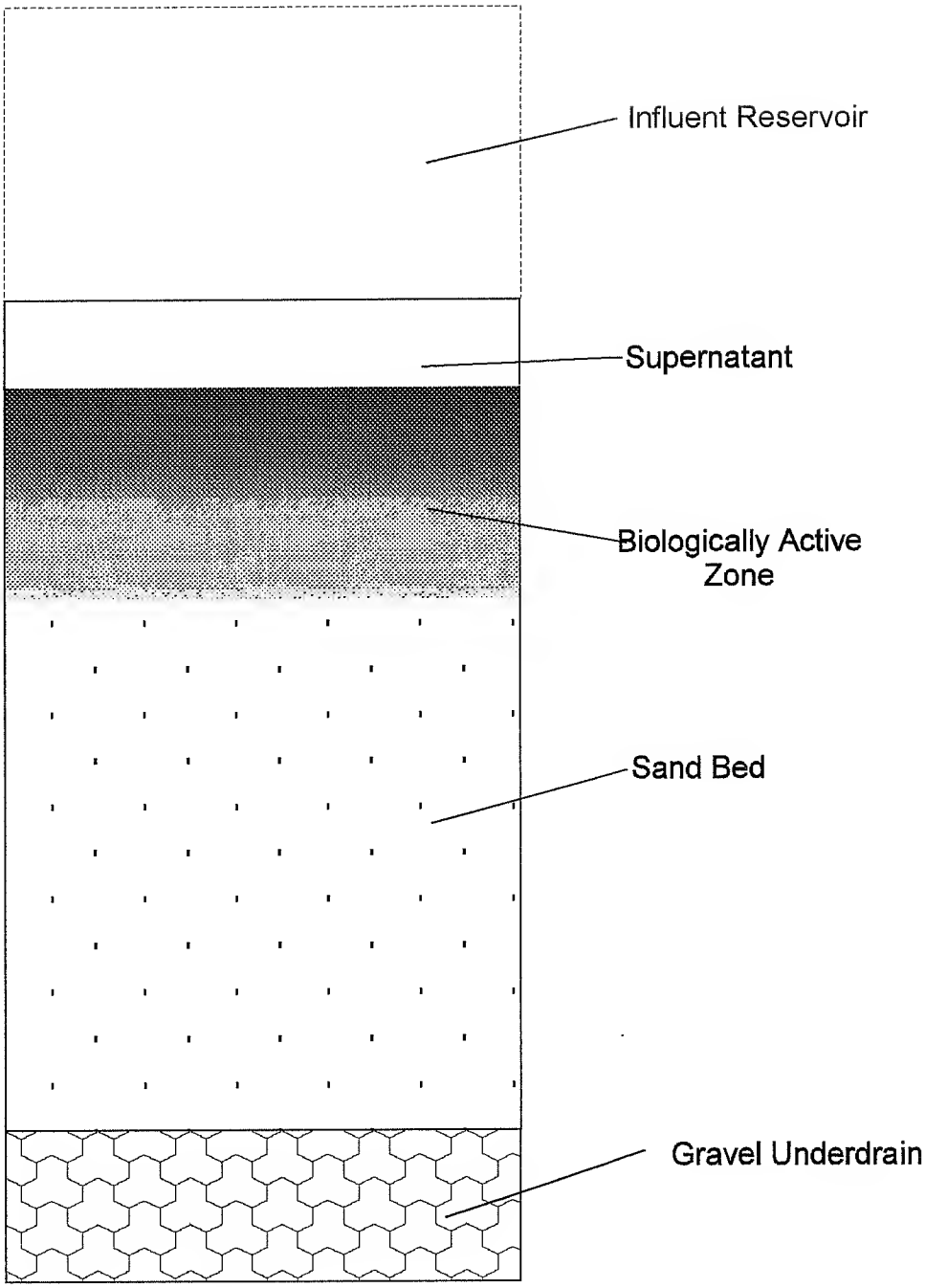

Figure 5.1 Component of an IOSS Filter

very still. The schmutzdecke is the layer of slime, mud and micro-organisms which develop on the sand surface. This is where the majority of contaminants are trapped. Below the schmutzdecke is the biological zone through out which biological life is present. In COSS filters this is reported as being 20 - 40 cm deep (AWWA 1991) however in IOSS filters it is predicted to be shallower around 5 - 10 cm deep. Below the biological layer are the layers of sand and gravel and the underdrain pipe which contain virtually no living microbes.

5.1.1 Changes in Influent

When the influent water is added to the influent water reservoir mixing occurs so that the water above the sand bed has uniform characteristics. During the pause time the water in the supernatant has a significant amount of oxygen and indicator organisms within it consumed. Even though the diffuser plate protects the sand it does not prevent the mixing of the influent and the supernatant water. The influent water is high in oxygen, nutrients and micro-biological life compared to the supernatant. Under normal circumstances the amount of supernatant water is small compared to the influent volume so the characteristics of the influent are almost unchanged. Once the influent reservoir has been filled the water begins to flow downward through the sand bed. Any motile predators either living in the supernatant or in the sand surface travel upward into the influent due to the new

more abundant food source. Many faecal indicator organisms and pathogens will be consumed here.

As the influent passes into the bed the water held in the filter over the pause time is pushed out. Initially the influent passing through the schmutzdecke is under a relatively large pressure head and the openings in the sand surface are relatively large. As the water passes through the schmutzdecke the larger particles are strained out reducing the size of the pore openings and causing an increase in the resistance of the sand to the flow of water. This combined with a declining head causes the flow rate to decrease. With the decreasing size of the pore openings and the decreasing flow rate the removal rate of contaminants in the filter increases.

During a filter run many more organics, pathogens and other contaminants are captured at the sand surface and in the biologically active zone then can be metabolised immediately. Some of the more easily consumed contaminants are oxidized rather quickly reducing the dissolved oxygen of the influent. As well some of the material from the previous run has only been partially oxidized and has now been broken down chemically which reduces the oxygen content of the water as it passes through the schmutzdecke and biological zone. Finally, the zoogeal, a slimy substance excreted by bacteria, has been depleted of oxygen over the pause time and diffusion from the higher oxygen content water replenishes this.

Eventually as the water level in the influent reservoir approaches the level of the outlet the water slows and finally stops. The dissolved oxygen in the water associated with the biology in the filter begins to decline as organics, pathogen and other cells are metabolised and broken down. In waste water treatment this is termed stabilisation (Modak 1971). Another term used for the metabolism of substrate is oxidation (Whitten and Gailey 1984). As this occurs a gradient is established in the filter causing the dissolved oxygen outside the biologically active zone to diffuse to the lower oxygen areas. In the sand bed a higher gradient is required to obtain the same oxygen flux since the area available for oxygen transfer is partially blocked by the sand grains. In the supernatant the gradient required is much less since the total horizontal area of the supernatant is available for oxygen transfer. After some time a gradient is established in the supernatant that satisfies the oxygen demand of the biologically active zone. The oxygen is used to reduce or stabilise the organics and pathogens in the filter and coverts these to both energy and physical growth of the organisms in the filter. A by-product of this process is the conversion of insoluble organics and substrates to soluble salts. This partially opens the pore openings in the filter.

In the supernatant the natural process of predation continues over the entire pause time further reducing the concentration of suspended contamination. In the lower

layers of the sand bed and in the underdrain the amount of contamination is small and natural die off due to a lack of substrate food and oxygen causes most organisms to die or move towards the more hospitable environment near the sand surface.

5.1.2 Changes in Effluent

Once the influent reservoir has been filled again the water that has spent the pause time in the filter begins to flow out. Initially this water is of very good quality since it has been cleaned by its trip through the sand and has had nearly 24 hours in which the natural die off and starvation due to lack of food has occurred. This first water coming from the filter spent the pause time in the underdrain and biologically inactive lower sand layers. Very little micro-biological life or substrate exists here so the dissolved oxygen is very similar to that of water passing completely through the filter in a single run.

Water that has spent the pause time in close association with the biologically active zone will have a significantly reduced oxygen concentration because of the metabolism of the large amount of organic substrate that has been trapped in this layer. Initially when the high head is first applied the pore openings are slightly larger than at the end of the previous run. This allows the unconsumed indicators

and contaminants to be swept through. A decline in oxygen level should thus be associated with a dip in effluent water quality as well. However, under normal operating conditions enough time is provided during the pause time to allow most of the contaminants to be consumed or destroyed.

After the water in the filter has been entirely replaced water which has been put into the filter in this run begins to flow out. This water will steadily improve in quality as the flow rate declines allowing more contamination to be removed.

5.2 Dissolved Oxygen Equation

Because the filter is aerobic, oxygen is required to break down and destroy organic contaminants and pathogens. The limiting factor in a filter which is operating intermittently is the amount of oxygen available for metabolism during the paused or stopped period. If only the oxygen already dissolved were available anaerobic conditions would develop but because of diffusion the depleted supply of oxygen in the biological layers can be replenished. If the resistance to diffusion becomes too great, like when a deep water layer is left over the sand bed, then the aerobic organisms will not obtain enough oxygen and the facultative organisms will begin to respire anaerobicly. The key is in how the supernatant behaves with respect to the diffusion of oxygen from the air to the biologically active zone.

5.2.1 *Development of an Equation*

The distance the oxygen is able to diffuse is limited by the resistance of the water in a similar way as insulation will slow the passage of heat through a wall. Two formulas govern the rate at which oxygen can reach the biologically active zone. First, there is the resistance of the air water interface and second, the resistance of the water layer to diffusion. The rate of oxygen transfer across an air-water interface is described by:

$$F_{O2} = K(C_s - C_B) \qquad \text{Eq. 5.1}$$

Where F_{O2} is the mass flux of oxygen across the interface, C_s is the saturation concentration of oxygen, C_B is the concentration of oxygen in the water just inside the interface and K is a constant related to the physical conditions of the system. K depends on temperature, and the resistance to mass transfer between phases. (Lewis and Whitman 1924)

Equation 5.1 was proposed in 1924 by Lewis and Whitman and is based on the two film theory they developed. Lewis and Whitman 1924 theorised that at a liquid-gas interface there developed a pair of imaginary layers or films, a gas film and a liquid film. The films are layers of aligned molecules through which only molecular diffusion occurs. This layer is like to a thin film of oil which forms an effective seal

between the air and water phases even though the fluids are vigorously mixed. This theory assumes that mixing in the body of the fluid is so rapid that the oxygen concentration in the liquid is uniform. When dealing with a slightly soluble gas like oxygen only the liquid film needs to be considered because the resistance of the gas film is negligible. Also because of the low resistance of the gas film the concentration at the interface can be assumed to be the saturation concentration of the liquid. (Lewis and Whitman 1924). Turbulence in the body of the fluid does not disrupt the layer but will cause it to become thinner (Haney 1954). The supernatant is not mixed in IOSS filters during pause times. This means that the transfer across the interface will not limit the rate of oxygen transfer into the supernatant, however the interface will provide some resistance to the transfer of mass.

The rate of oxygen transfer is not limited by resistance at the interface because in situations where the liquid is not mixed, like the water in IOSS filters during pause times, the rate limiting step is diffusion through the water to the biological layer (Churchill et al. 1962). The governing equation is Fick's Law of Diffusion and is written:

$$F_{O2} = -D\nabla C \qquad \text{Eq. 5.2}$$

Where F_{O2} is the mass flux of oxygen through the standing water layer, D is the diffusion coefficient, ∇ is the differential operator, and C is concentration (Huntington 1990). In this case the oxygen demand is assumed to be uniform over the surface

of the sand bed and so the problem is considered one dimensional. Fick's law then becomes:

$$F_{O2} = -D\frac{dC}{dy} \qquad \text{Eq. 5.3}$$

It is assumed that the oxygen demand of the biological layer is constant and that the limiting condition is steady state, that is when the gradient across the standing water layer is just sufficient to drive the required mass flux of oxygen to supply the biological layer. The definition sketch is shown in Figure 5.2. From Figure 5.2 the following formula for the variation of oxygen concentration with water depth was developed:

$$C = \frac{C_L - C_B}{y_L} y + C_B \qquad \text{Eq. 5.4}$$

where C is the concentration at depth y, y is depth below the water surface, C_B is the concentration at the water/air boundary, the concentration at the biological layer is C_L and y_L is the distance between the water surface and the biological layer. Substituting this into Equation 5.3 and taking the derivative results in the diffusion equation for this case,

$$F_{O2} = D\frac{(C_B - C_L)}{y_L} \qquad \text{Eq. 5.5}$$

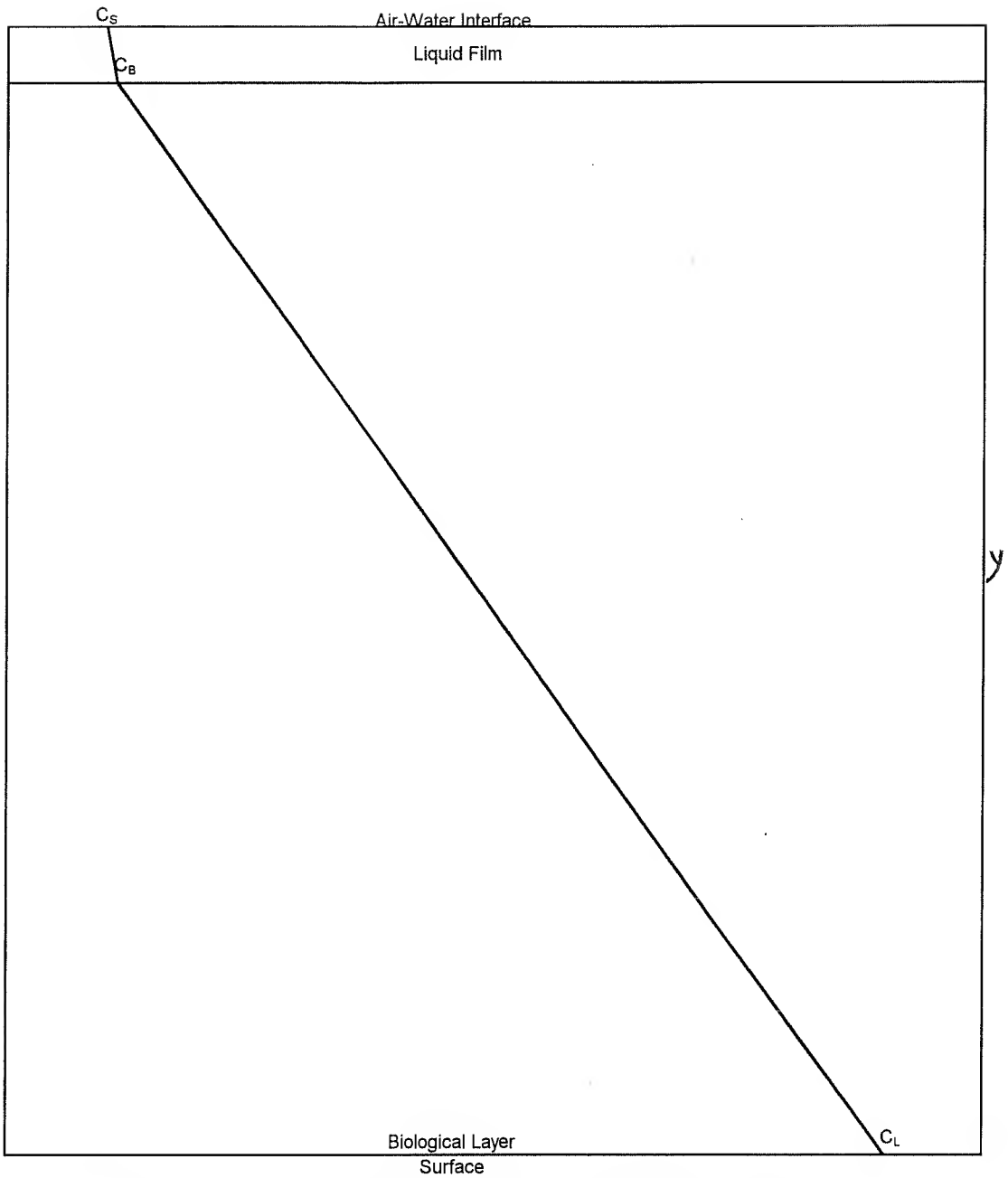

Figure 5.2 Variation of Dissolved Oxygen in IOSS Filter Supernatant

For the system to remain aerobic the rate of oxygen use must not exceed the rate of diffusion. It is conservative to use this equation since it assumes that no mixing occurs in the fluid. In fact differences in density, temperature, gradients, movement of air across the surface, micro-biological activities and other disturbances of the filter will cause some mixing, allowing oxygen to be transferred more easily. This could be accommodated by increasing the diffusion coefficient D to account for the mass movement produced by this effect or by adding a term describing mixing in the supernatant. An estimate of the mass flux of oxygen can be made by adding the interface resistance to the diffusion resistance. This is done by solving one of Eq. 5.1 or Eq. 5.5 for the concentration at the boundary C_B and substituting into the other governing equation. This gives:

$$F_{O2} = \frac{DK}{Ky_L + D}(C_S - C_L) \qquad \text{Eq 5.6}$$

Equation 5.6 describes the transfer of oxygen through the supernatant to the biological layer in IOSS filters. Although no information regarding the utilisation rate of oxygen by the microbes in slow sand filters could be found, a value may be estimated from Eq. 5.6. Saturation of oxygen in water is approximately 9.17×10^{-3} mg/cm^3 at 20 °C (Peavy et al. 1985). The lowest allowable concentration of oxygen in the biological layer is 1×10^{-3} mg/cm^3 if anaerobic conditions are to be avoided. The diffusivity of oxygen in water is 6.48×10^{-2} cm^2/hr at 20 °C (CRC 1970). The

film resistance K for oxygen from oxygen into unmixed water is 0.38 cm/hr at 20 °C (Haney 1954). These values allow us to calculate a oxygen demand flux rate for the biological layer.

$$F_{O2} = \frac{(0.38)(0.0648)}{(0.38)(5) + 0.0648)}(9.17x10^{-3} - 1.00x10^{-3}) \qquad \text{Eq. 5.7}$$

$$F_{O2} = 1.02x10^{-4}\ mg/cm^2/hr \qquad \text{Eq. 5.8}$$

The effect of eddy diffusion and convection are also significant in the mass transfer across the water layer even though the layer is not mixed. This makes the estimate conservative since any mixing would decrease the resistance allowing deeper water or increased biological oxygen consumption. No information on the oxygen utilisation rates of slow sand filters was discovered in the literature review. Even if this parameter has been measured for particular filters because of differences in the ambient parameters of temperature, seasonal variability, and raw water quality, oxygen utilisation rates cannot be transferred between filters. In addition, since no research exists on the IOSS filter process the oxygen utilisation rate, and diffusion coefficient, which includes convective mixing, and the allowable water depth must be established by experiment. Although this calculated oxygen flux rate is a conservative maximum, to allow a biological layer to some depth in the sand bed it is necessary to maintain an abundant supply of oxygen to allow the biological layer to thrive and so a minimal water layer should be used.

5.2.2 *Temperature Effects*

The allowable water depth above the sand bed will be significantly influenced by temperature. Both the K and D increase with temperature providing less resistance to the transfer of oxygen. The following equation describes how K varies with temperature (Peavy et al. 1985):

$$K_T = K_{(20)} (1.016^{T-20}) \qquad \text{Eq. 5.9}$$

Where T is temperature in degrees Celsius. The diffusion coefficient varies according to (CRC 1970):

$$D_2 = \frac{T_2 \mu_1}{T_1 \mu_2} D_1 \qquad \text{Eq. 5.10}$$

Where T is temperature in degrees Kelvin and μ is viscosity in N s/m^2. The variation of these parameters with temperature are shown in Figure 5.3 and Figure 5.4 respectively. This reduction in resistance is offset by both the large decrease in the saturation concentration of oxygen in water and the increase in the oxygen utilisation rate of the microbes with temperature. At 20 °C the saturation concentration of oxygen in water is 9.17 mg/l. At 30 °C this is reduced to only 7.63 mg/l (Peavy et al. 1985). Also, the oxygen utilisation rate of microbes will nearly double with each 10 °C increase in temperature (Curry 1992, Peavy et al. 1985). The variation of oxygen saturation and microbe oxygen demand are shown in Figure 5.5 and Figure 5.6. If the oxygen supply rate is now estimated for the filter with a 5

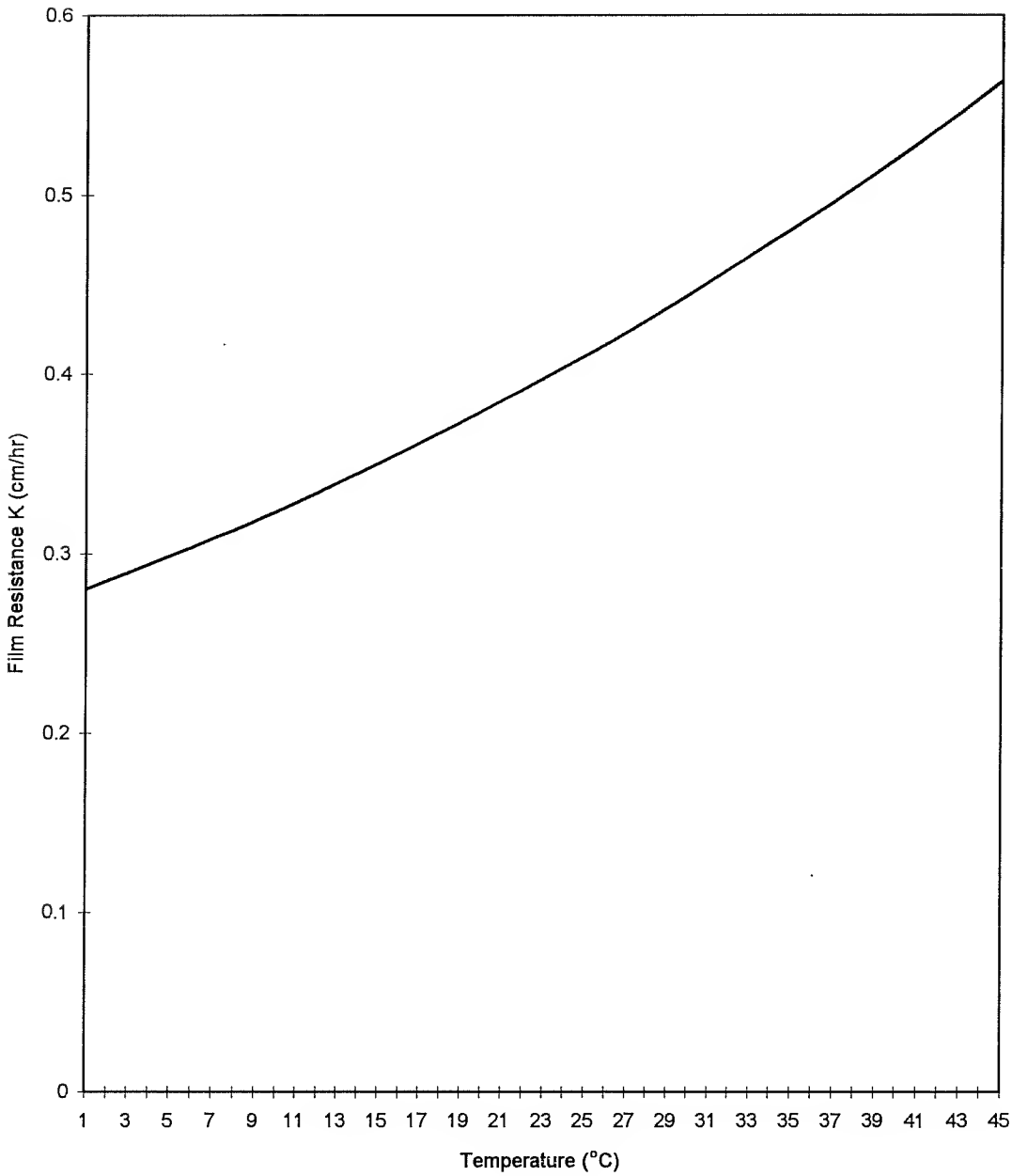

Figure 5.3 Variation of Film Resistance K with Temperature

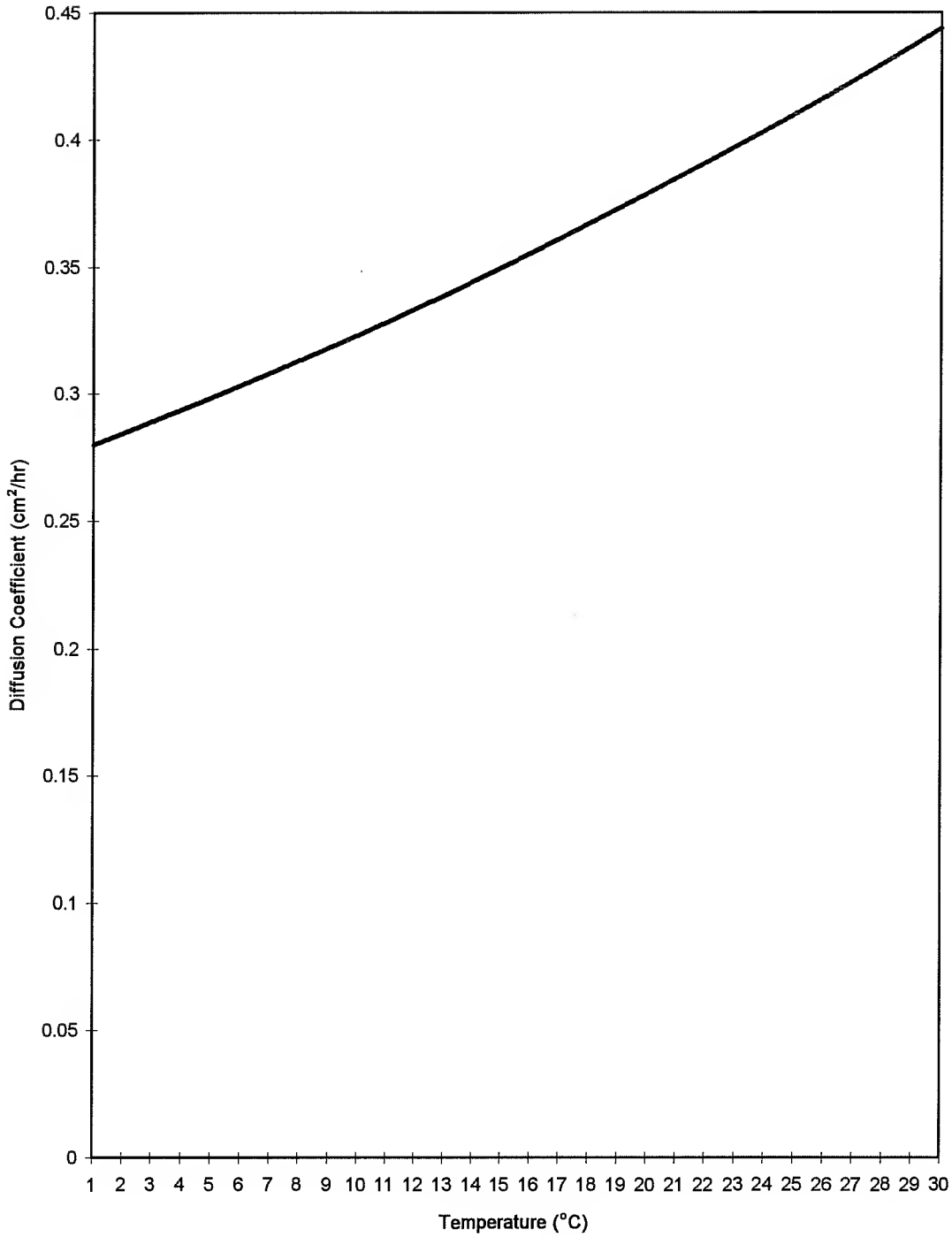

Figure 5.4 Variation of Diffusion Coefficient D with Temperature

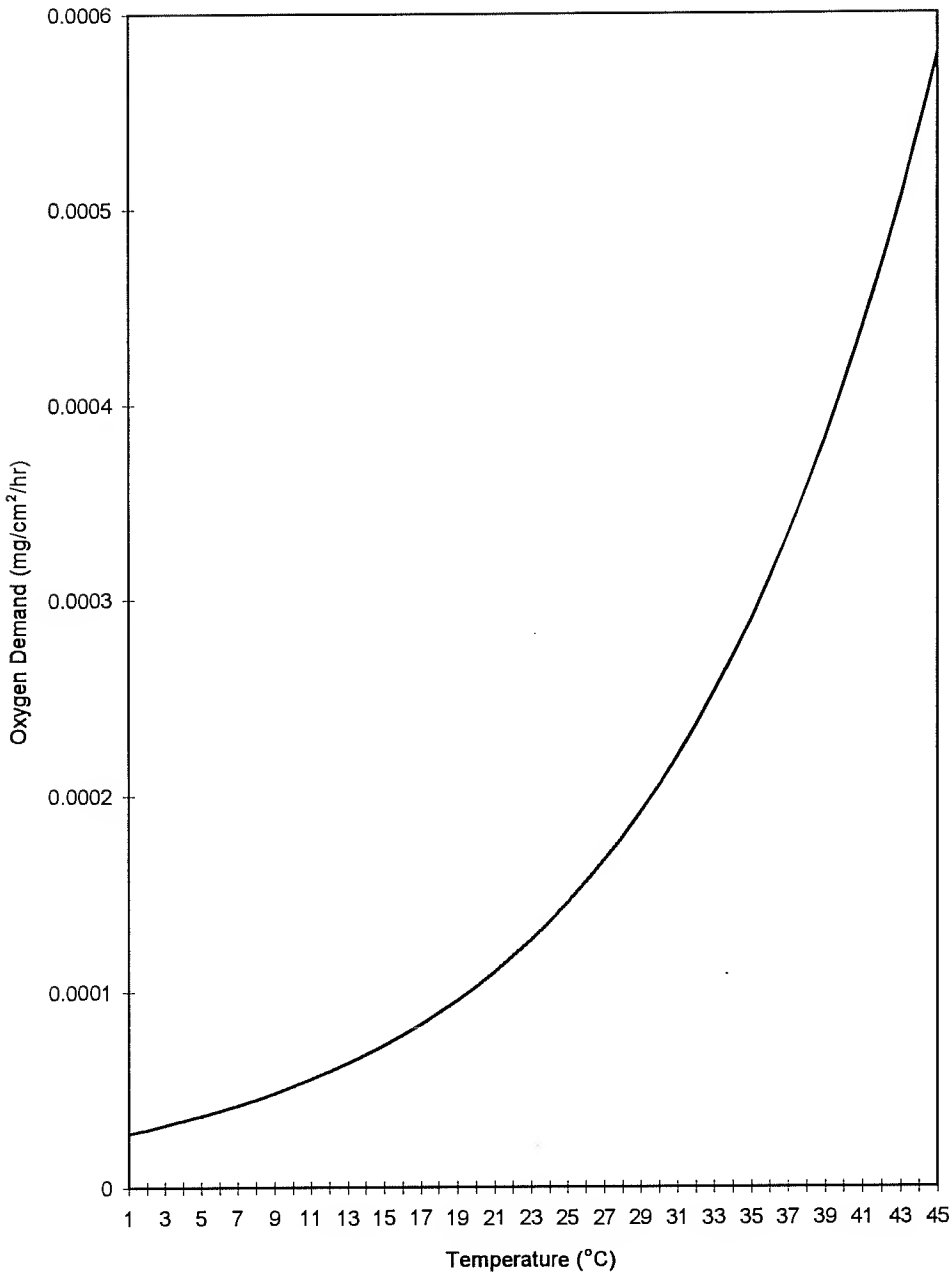

Figure 5.5 Variation of Microbiological Oxygen Demand with Temperature

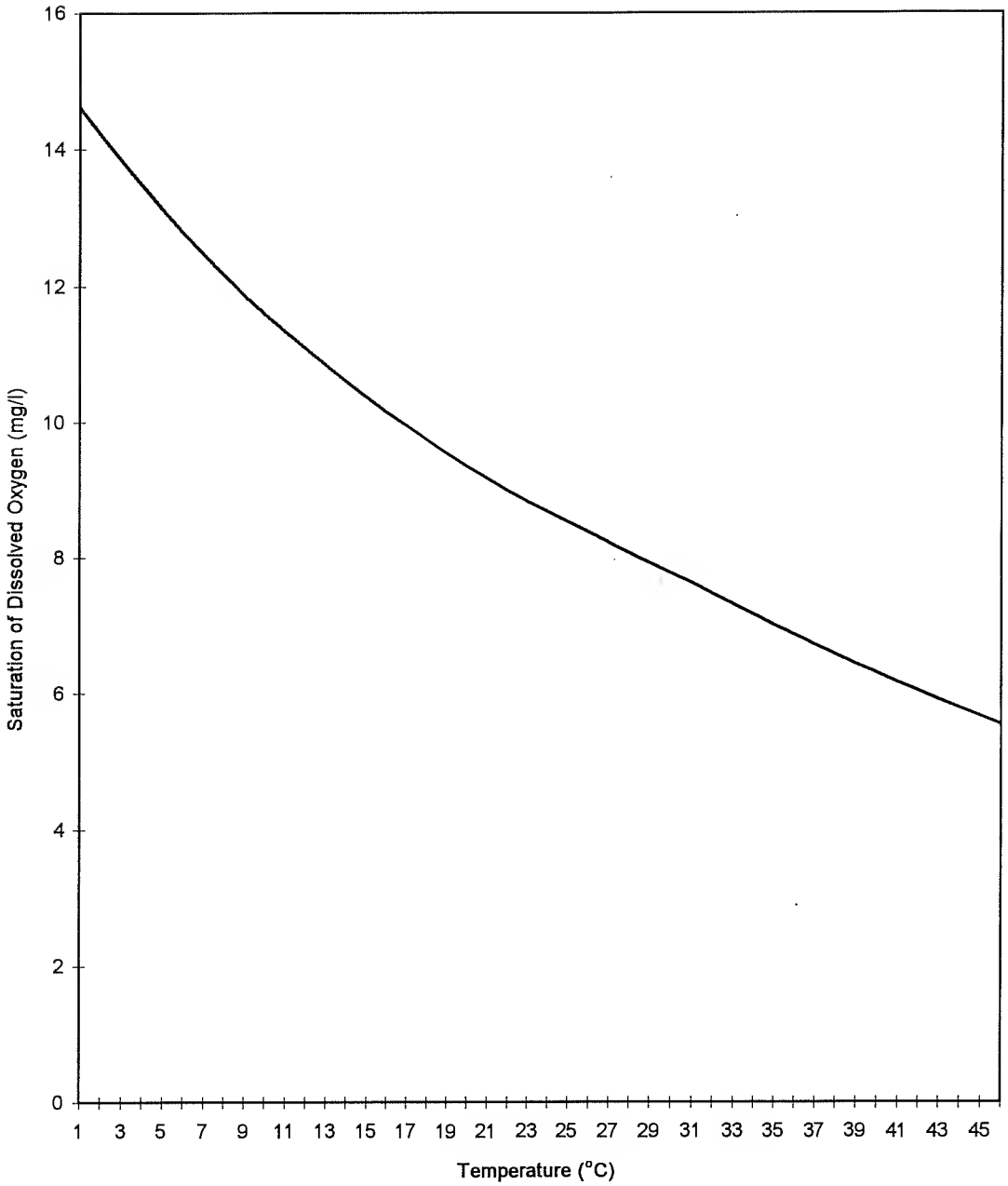

Figure 5.6 Variation of Saturation Oxygen Concentration with Temperature

cm standing water depth for a normal temperature of 30°C it is now 1.09 x 10^{-4} mg/cm^2/hr. Figure 5.7 shows how the maximum oxygen supply rate in the filters is predicted to change for filters with a 5 cm standing water depth established at different temperatures. Figure 5.7 shows the optimum temperature for a 5 cm standing water depth filter is predicted to occur at around 30°C.

The effect of temperature on the allowable water depth is shown in Figure 5.8 based on two oxygen usage rates calculated for a 5 cm standing water depth filter. If a filter established at some temperature is suddenly moved to a warmer environment the water depth must be decreased to provide the same oxygen flux. The critical effect of water depth on filter performance and oxygen utilisation is shown in Figure 5.9. Because the maximum possible oxygen usage rate increases exponentially as the depth of the standing water layer decreases the most shallow water depth possible is most desired. However, the sand surface must not be disturbed because this would cause the biological layer to be below the sand surface. If the sand has a typical porosity of 40% the gradient in the sand for the same oxygen flux is more than 2 times that for the unobstructed supernatant.

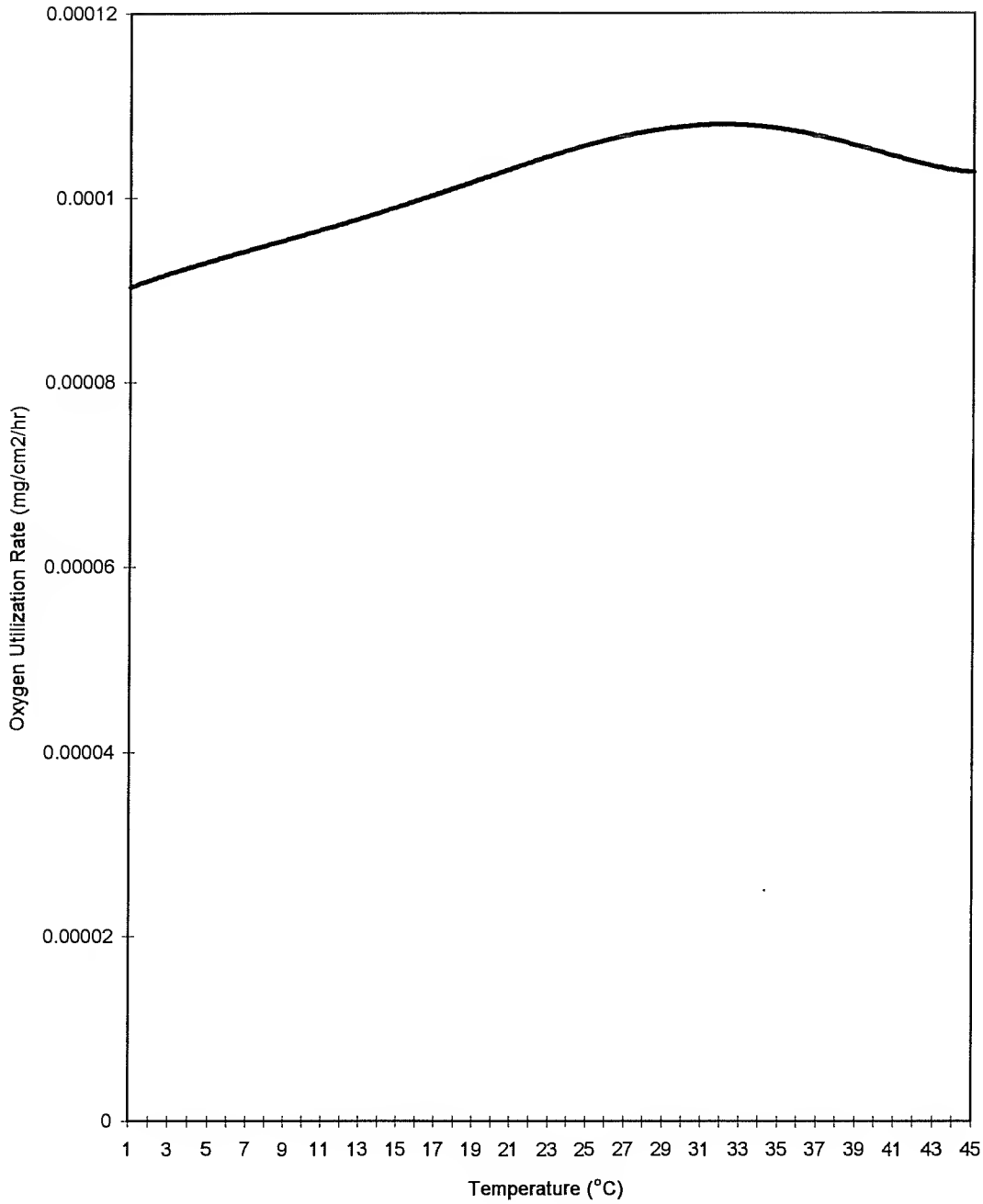

Figure 5.7 Maximum Oxygen Utilization Rates for Filters Established at Varying Temperatures

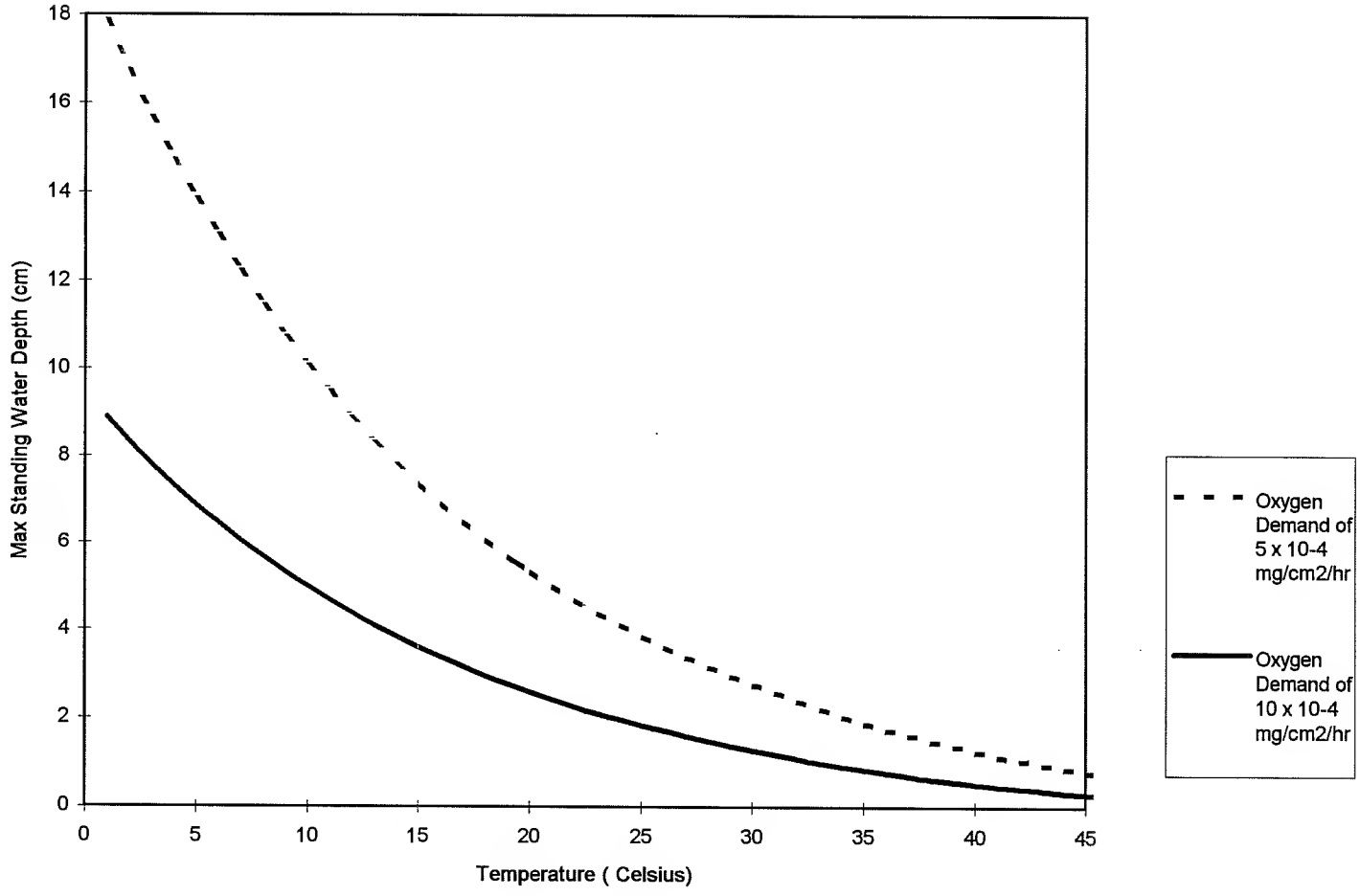

Figure 5.8 Theoretical Standing Water Depth against Temperature

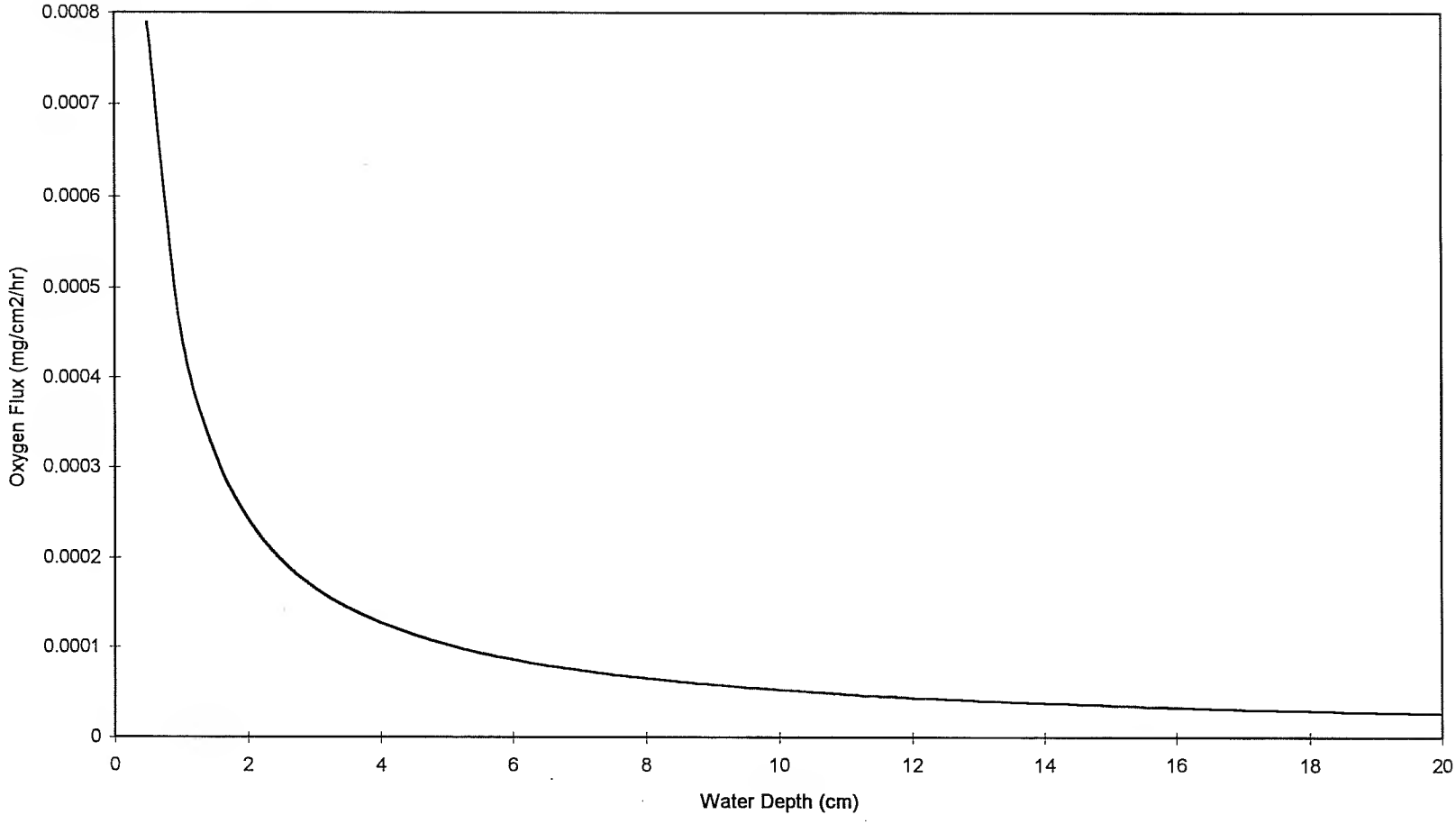

Figure 5.9 Maximum Oxygen Fluxes at 20 °C with Varrying Water Depth

5.3 Theoretical Expectations

The concentration of oxygen at the top of the biologically active zone C_B can be viewed as a measure of stress or effort the microbes of the filter must exert to produce a gradient which will supply their oxygen needs. Increases in temperature and standing water depth will require a smaller C_B to supply the required oxygen. This basic theory has not considered the effect dissolved oxygen concentrations will have on the rate of metabolic reaction although it is generally known that reaction rates are proportional to the concentrations of the reactants. It can be assumed that larger concentrations of oxygen at the biological layer will also increase the utilisation rate of oxygen.

Because oxygen is a limiting factor in the IOSS filter process and the supply of oxygen is limited by diffusion from the surface, it is expected that the micro-organisms in the filter will be more closely confined to near the surface of the sand bed. The limited oxygen and substrate for respiration will make it very difficult for organisms to survive very deep inside the sand bed. Additionally the area available for oxygen to diffuse in the sand bed is reduced to the pore openings in the media about 30% of what is available in the supernatant. Organisms that are motile, able to move, will migrate towards the surface of the sand during stagnate periods in search of better living conditions. All this should cause the biologically active zone

in IOSS filters to be thinner than in continuously operated filters. Because the biologically active zone is thinner, the contact time between the biofilms and water during filter runs will be less at conventional rates of filtration. The contact time affects the removal efficiency of the filter since it takes time for contaminants to be absorbed and metabolised out of the water. If this is true, slower filtration rates may be required to produce water of similar bacteriological quality to continuous slow sand filters. But, research by Bellamy et al. (1985a) on continuous filters demonstrated that COSS filtration rates may currently be conservative since a change in filtration rate from 0.04 m/h to 0.40 m/h changed the coliform removal efficiency from 99.96% to 98.98%. As a trade off to requiring slower flow rates, IOSS filters may not require the same depth of sand as required in COSS filters. If the microbiology is confined to a more shallow depth of sand than 40 cm then a more shallow sand bed can be used. However, the more shallow the standing water depth is during pause times, the deeper the biological layer will penetrate the sand. This will cause larger oxygen demands since the biologically active layer is more concentrated near the surface and extends further into the sand bed.

During the pause time the water in contact with the biological layer should have a significant amount of the contaminants within it removed. Oxygen will not be a limiting factor in a properly designed IOSS filter so that substrate, food for the microbes, becomes the limiting component. If the pause time is extended for a long

enough period micro-organisms will eventually use all the substrate available to them and then will die. This again will cause a marked reduction in the removal efficiency of the filter.

The effect of sand bed depth is an important design parameter from an economic point of view and also due to the fact that the hypothesis predicts that sand bed depth should have a minimal effect on the bacteriological quality of the effluent. The relative thickness of the biologically active zone should decrease with increasing water depth during pause times. A thinner biologically active zone would have a lower oxygen utilisation rate and so would survive under a greater depth of water.

Consistent operations are more important in IOSS filters than in the continuously operated ones. The condition of the filter during the pause time must not change significantly. Take for example an IOSS filter operated with a standing water depth of 5 cm. For some reason this standing water depth is increased by 5 cm and then the filter is allowed to adjust to the new situation before the standing water depth is again increased. The density and depth in which the microbes living in this filter are controlled by the situation in which they established themselves. That is they are limited by the supply of oxygen. It takes time for the filter biology to adapt to the new situation. Given time as the biology of the filter adjusts to the new water depth the bio-layer will move upward in the sand bed and the oxygen demand rate and thus

the oxidation and metabolism of contaminants will decrease. This will continue with further increases in standing water depth until the filter becomes a non-living system were very little life exists in the sand bed because very little oxygen is available and the oxygen differential needed to provide any significant oxygen supply rate will require anaerobic conditions in the biologically active zone.

In another hypothetical situation a sudden increase of water depth in the normal 5 cm standing water depth filter would result in a filter that would consume oxygen at its normal rate except that a much higher differential is required to obtain a similar gradient and thus allow diffusion to provide enough oxygen to allow the filter to function properly. This may mean that, at least in a portion of the sand bed, not enough oxygen will be available and the facultative organisms will start metabolising substrate anaerobically. If the water level is too deep the entire biologically active zone will become anaerobic causing taste and odour problems.

5.4 Specific Objectives

The specific objectives will be required to both accomplish the general objectives of 1.1 and to limit the scope of the research since the field is virtually unexplored. First a water source was chosen that included a diversity of life and measurable contamination. This water source had to be accessible and relatively consistent in

quality. Next, a protocol had to be developed to gain as much information as possible with the equipment and budget available. The testing had to provide information about the working of the filter during operation and what occurred in filter during pause times or resting periods.

6.0 APPARATUS

The art of art, the glory of expression and the

sunshine of the light of letters, is simplicity.

- Walt Whitman

For the laboratory examinations of the filter a concrete filter made using a set of forms later taken to Nicaragua to demonstrate construction techniques was used. The laboratory filter had a 35 cm sand bed depth and a standing water depth of 12.5 cm. Figure 6.1 shows the dimensions of the laboratory filter.

The sand for this filter had a d_{10} of 0.17 mm and an UC of 3.6. The gradation analysis is included in Figure 6.2. The gravel underdrain used 14 mm construction gravel from the Civil engineering concrete laboratory. Both the sand and the gravel for the filters were taken to the Bow River and were washed with water from the main channel to simulate as far as possible normal installation and operating conditions. First, the filter was emptied of any material which may have fallen into it during construction or transportation. Next the underdrain was checked to ensure it was installed properly and the holes were oriented downward. The empty concrete filter was then placed in the desired location since after it was filled with sand and gravel it would be difficult to move. Next gravel was added until it covered the underdrain tube by about 5 cm. A five gallon pail of water was then added to prevent air from

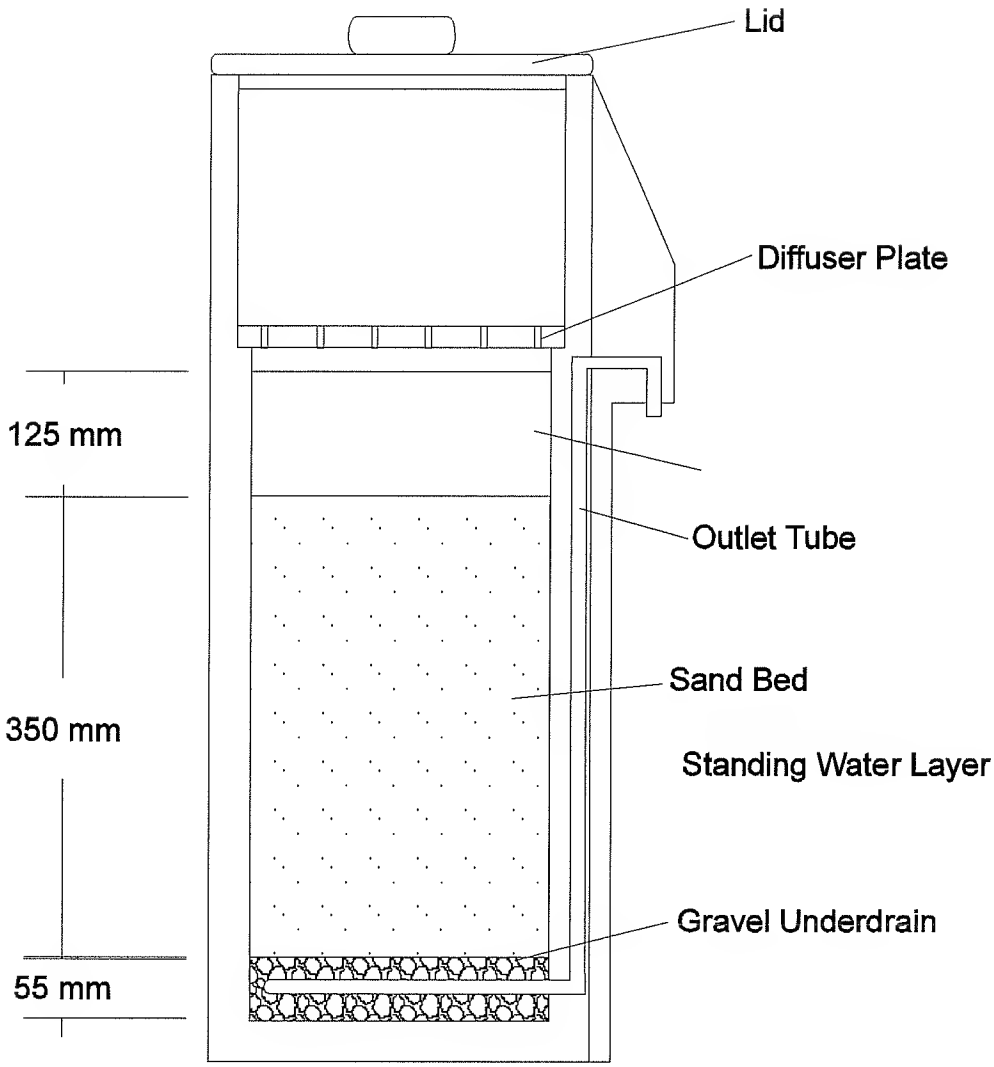

Figure 6.1 Sketch of Laboratory Filters

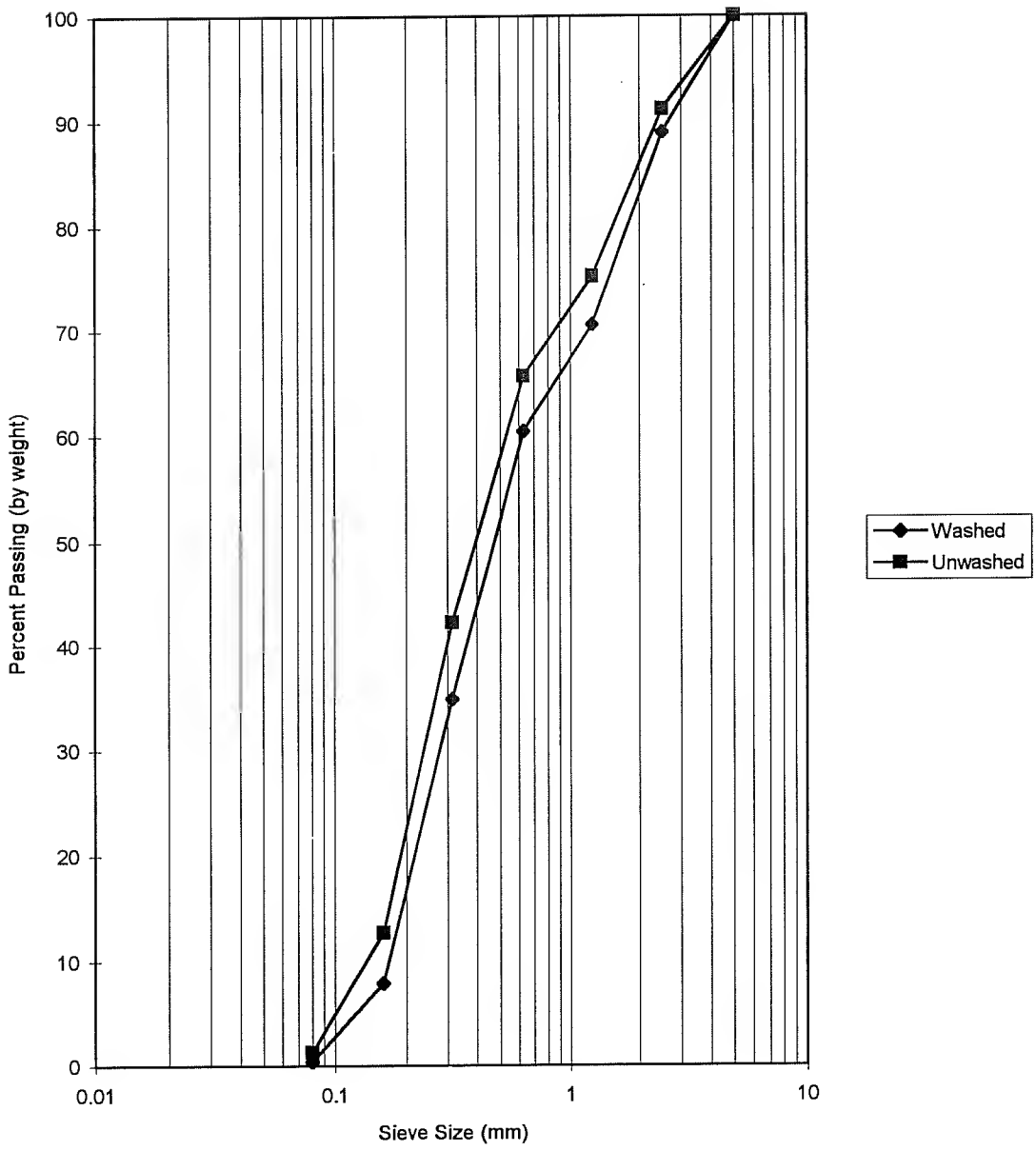

Figure 6.2 Gradation Analysis of Laboratory Filter Sand

being trapped in the sand while it was being added. The surface of the gravel layer was levelled and the sand was added to a depth of about 15 cm below the diffuser plate support and levelled. Next the diffuser plate was placed. Water was then run through the filter. Initially the water produced by the filter was cloudy but after 40 litres of water had been run became clear. The amount of water run through the filter to clarify the filtered water depends on the degree to which the sand had been washed.

Water for running the filter was obtained daily in two, twenty litre carboys. Initially, water for the filter runs was taken from the main stream of the Bow River, however, this water did not contain a sufficient level of faecal coliform bacteria to allow accurate testing so later the collection location was moved to a nearby duck pond. On October 12 the duck pond had been drained so the main channel of the bow was again used as a water source. The use of a natural water source containing a reasonable level of contamination was necessary to provide the natural diversity of life needed to establish and maintain the biological component of the filter. Also, this was the best choice considering the difficulty associated with producing a simulated source and because the use of spikes in the influent will effect results in unpredictable ways.

7.0 EXPERIMENTAL PROGRAM

At first people refuse to believe that a strange new thing
can be done, then they begin to hope it can be done,
then they see it can be done - then it is done and all the
world wonders why it was not done centuries ago.

- Frances Hodgson Burnett

The intensive laboratory study was undertaken to explain and expand results encountered until this time. In addition to faecal coliform testing an expanded physical analysis of the filtered water was undertaken to determine the effect the filter had on pH, dissolved oxygen, and electrical conductivity. Although relatively free of contamination the bow river was used as a water source.

The theory of intermittently operated slow sand filters pointed out three main variables which uniquely affect intermittently operated slow sand filtration. These were water depth above the sand bed during pause times, sand bed depth and length of pause time. The research concentrated on these parameters and some relationships to water quality were determined.

The primary measure of filter performance was faecal coliform removals. Dissolved oxygen was important in testing the theory of intermittent operation and was also

performed in conjunction with the bacteriological testing. Because the filter skin and biological layer effect the development of head loss in the filters, head loss was monitored to indicate biological development. In addition, turbidity, pH and electrical conductivity were measured so a more general picture of the filtration process effects on water quality could be determined.

7.1 Laboratory Testing Program

This filter was intensively studied. Daily, the filter was run with 25 litres of influent water. Several samples were taken through out each filter run after 1, 5, 10, 15 and 20 litres had passed through the filter. Each sample was tested for faecal coliforms (duplicate tests), turbidity, pH, dissolved oxygen, electrical conductivity and temperature. At each sample point the flow rate and head were measured to allow the calculation of hydraulic conductivity.

The run normally proceeded as follows. Initially, water was collected in two twenty litre carboys from the duck pond in Bowness Park. The water was then transported back to the university and the temperature allowed to adjust for about an hour before being added to the filter. Initially the diffuser plate was removed and a turbidity sample of the supernatant was taken in a 20 ml ampoule used for this purpose. Next the supernatant was gently stirred to make sure the dissolved oxygen and faecal coliforms in the supernatant were evenly distributed. A sterile 250 ml

polypropylene sample bottle was then filled with supernatant water for the micro-biological tests and a clean 400 ml beaker was filled with water for the physical measurements. The diffuser plate was then replaced in the same orientation as original.

The water from the carboys was then added to the supernatant reservoir above the sand bed. First, the carboys were vigorously shaken and then poured into the supernatant reservoir. From the stream flowing out of the carboy a sterile sample bottle and a clean 400 ml beaker were filled with water for the influent micro-biological and physical testing.

Once water had been added to the supernatant reservoir, water started to come from the outlet. A bucket graduated with 1 litre increments was allowed to fill to one litre. When the one litre mark was reached, a graduated cylinder and watch were used to measure flow rate and the head was measured with a tape measure. A 400 ml beaker was then filled for the physical analysis and a 250 ml sterile sample bottle was filled for the micro-biological test. This process was repeated after 5, 10, 15 and 20 litres had passed through the filter. Adjustments for the amount of water removed for sampling were made when determining the volume of filtered water.

As the beakers were filled they were examined for physical parameters. Before adding water to the filter and beginning testing, the instruments were calibrated by

carefully following the manufacturers instructions. First , the beaker was stirred and a 20 ml ampoule was filled for the turbidity test. The exterior of the ampoule was then dried and cleaned using a Kim (low lint) wipe. The turbidity was then measured using a Digital Direct Reading Turbidimeter provided by Hoskins Scientific. Next a one inch magnetic stirring bar was added to the beaker and the beaker placed on a magnetic stirrer. The sample was stirred at the same rate for all samples. The probes for DO and the pH as well as a temperature probe attached to the pH meter were held in a specially built holder allowing them to be used as a single unit. This was placed in the stirred beaker. A dissolved oxygen meter (Hanna Instruments HI 9143) and a pH meter (Hanna Instruments HI 9025C) were used to measure these parameters. After the temperatures on the two probes had stabilised, the pH, DO and the respective temperatures measured by each instrument were recorded. The electrical conductivity was then measured and recorded using a Hanna Instruments EC meter HI 3291. Finally the sample was removed from the magnetic stirrer.

The samples collected for the faecal coliform analysis were analysed following the requirements of Standard Methods 16th Edition (APHA 1985). If tests were not conducted within 1 hour of sample collection the samples were refrigerated until the test. Based on the previous test of the same sampling point, sample dilutions were determined. The sample was then filtered through a 0.45 μm pore opening membrane filter. The filter was part of a micro-biological monitor Sin-Can part no. 8025 which was used because it reduced the time required to conduct the test,

sterilise equipment and also reduced the chances for error since no membrane transfers were needed. The faecal coliform counts for the intensive testing are averages of pairs of replicate plates. The media was then added to the monitor. Media used in this experiment was made from dehydrated m FC Broth Base media produced by Difco. Media was prepared by following the instruction given on the label. Media consistency was insured by conducting overlap tests before beginning to use a new batch of media. The test plates were then incubated for 20 to 24 hours at 44.5 °C and counted. Faecal coliform colonies grown on this media are various shades of blue while colonies of non-faecal origin are grey or cream coloured (APHA 1985)

After 32 days of normal operation several special experiments were performed with several days of normal operation between them to allow the filter to again achieve a relatively normal state. Two extended pause tests of two days and four days as well as an constant head run of 40 litres and a filter scraping were performed in the intensive study.

8.0 RESULTS AND DISCUSSION

If one is lucky, a solitary fantasy can totally transform

one million realities.

- Maya Angelou

Intensive testing of a intermittently operated slow sand filter was conducted from August 30 to November 15, 1994. Over the time period before day 32, the test consisted of a 25 litre run of water collected from a natural surface water source, the Bowness Park Duck Pond. A volume of 25 litres was chosen to give total replacement of the 22 litres of water within the filter over a pause time. The replacement of the water in the sand was most important because the supernatant was mixed with the new influent water and as a result the process was not considered slug flow except in the sandbed. The volume of water held in the supernatant was 11-15 litres, in the sand bed 9-13 litres, and 2 litres in the gravel and underdrain tubing. These volumes were calculated assuming the granular material was 30-40% voids. As a result the location of the various sample points during the pause time could be determined.

Tests to more fully evaluate the characteristics of the filter were conducted with periods of normal operation between to allow the filter to recover to an relatively normal state. Special experiments included a 2 day and 4 day extended pause test,

a constant head run and the evaluation of filter scraping. Complete data was not collected before the tenth day of the test because during this time the sampling procedures were standardised and the realisation of the special characteristics and variations through the run required more data be collected.

8.1 Faecal Coliform Test Results

Laboratory tests of the field prototype show high removal rates for faecal coliform bacteria. Removals for faecal coliforms are shown in Figure 8.1. Even though there is significant variation of removal rates due to influent contamination fluctuations, removals are consistently more than 90% for faecal coliforms.

Figure 8.2 is a plot of faecal coliform counts for the various sample points over the period of normal operation. The plot shows the high variation of water quality of the surface source. The figure also shows the larger contamination of the still duck pond water source, used from days 10 to 42, and the main channel of the Bow River used outside of this time period. Influent coliform counts vary considerably with time from a low of 0 to a high of more than 1300. High faecal coliform spikes occurred at regular intervals generally coinciding with holidays and weekends because the water source was in a public park. The highest influent peaks occurred during weekends with good weather since the park received the highest use during these times. These types of variations are consistent with what is expected from surface

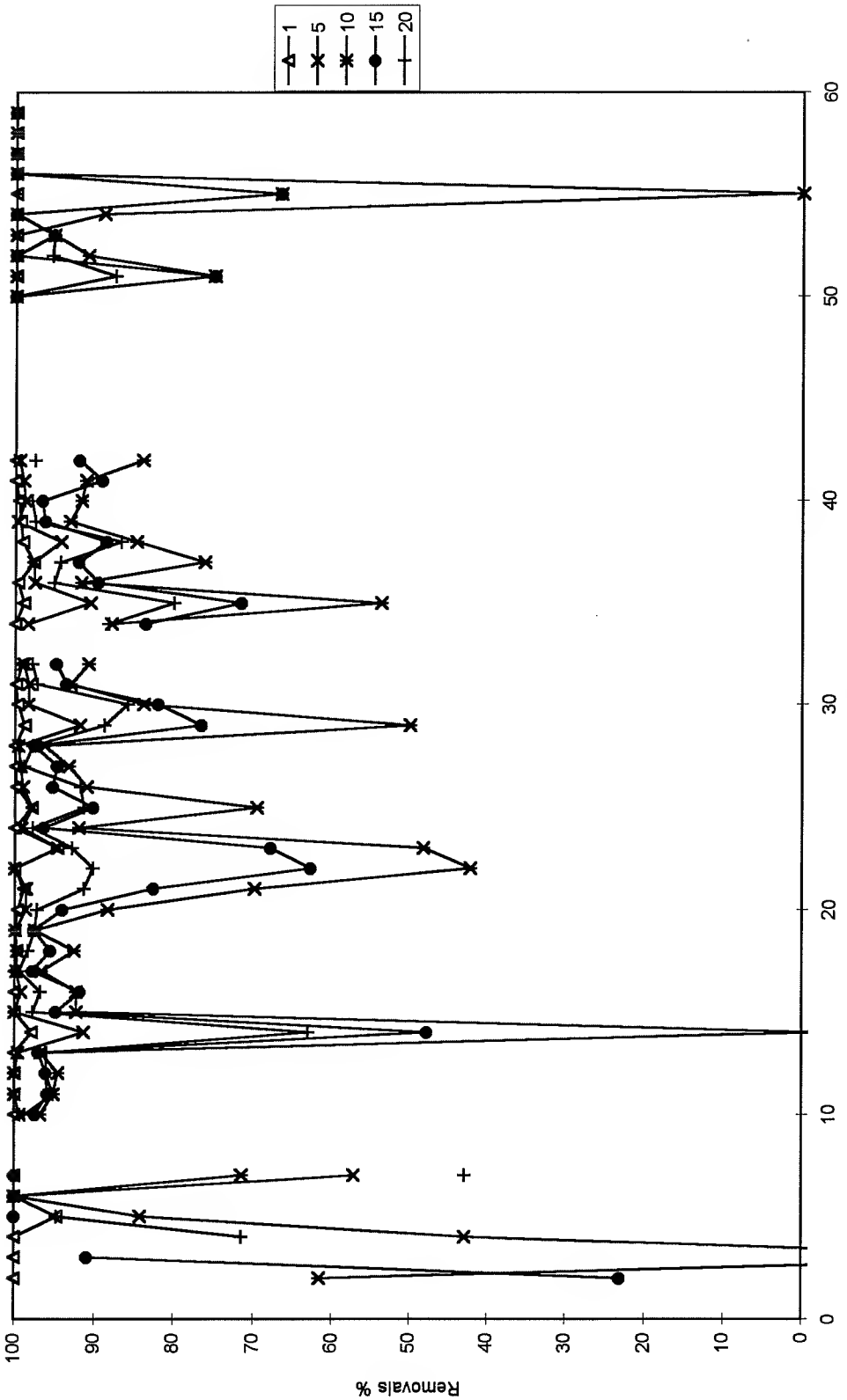

Figure 8.1 Removal Rate of Faecal Coliforms with Time

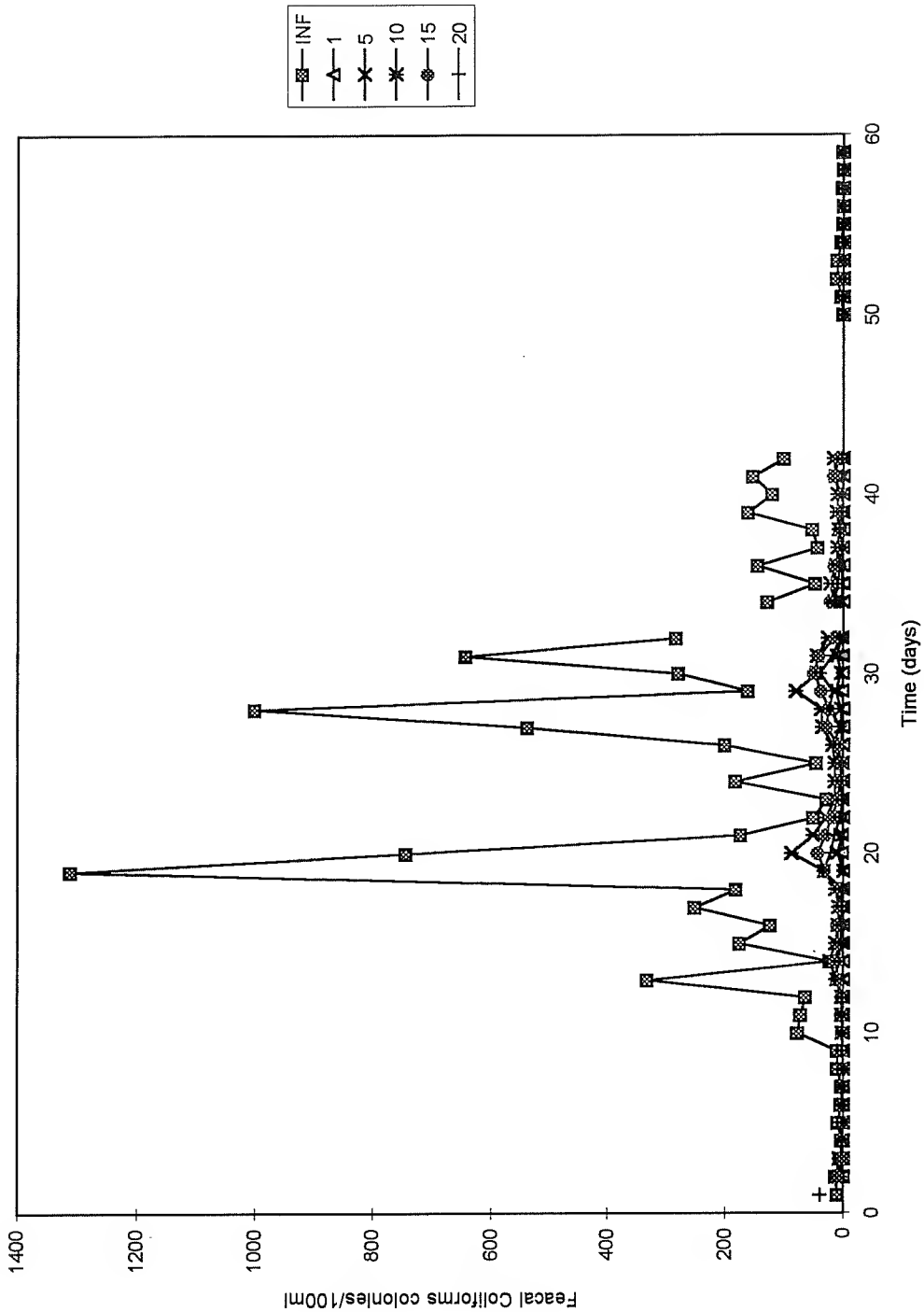

Figure 8.2 Faecal Coliform count over Time

water sources. Increases in and variations in faecal coliform counts will coincide with precipitation events, animal and human activity, changes in flow rate and temperature changes. Although several water sources had been considered this natural water source was chosen because of its natural diversity of life and its relatively high faecal contamination. The fluctuations in the influent water quality combined with an observed carry over effect caused the massive and seemingly erratic percentage removal rates shown in Figure 8.1. The carry over effect will be fully described later.

Figure 8.3 is a plot of cumulative faecal coliform counts for the various regularly taken samples for the time period 10 to 42 days. The slopes of the linear trend lines gave average data for faecal coliform counts for this time period. The cumulative plot is useful since it smoothes the effects of influent variations. Figure 8.4 is a plot of the typical faecal coliform counts over a single run taken from the slope of the cumulative plots. The initial supernatant value was calculated from the known concentration, volume of the supernatant after the run and the volume and concentration of the influent. The removal rates calculated from these averages ranged from 99.7% to a low of 91.1% Figure 8.5 is a plot of the average removal rate with volume run. The averaged run data shows the characteristic drop in removal efficiency after 10 litres of water has passed through the filter. The volume of water held in the sand bed over a rest period is about 11 litres. An integration of the influent and effluent faecal coliform counts with respect to volume, the plot

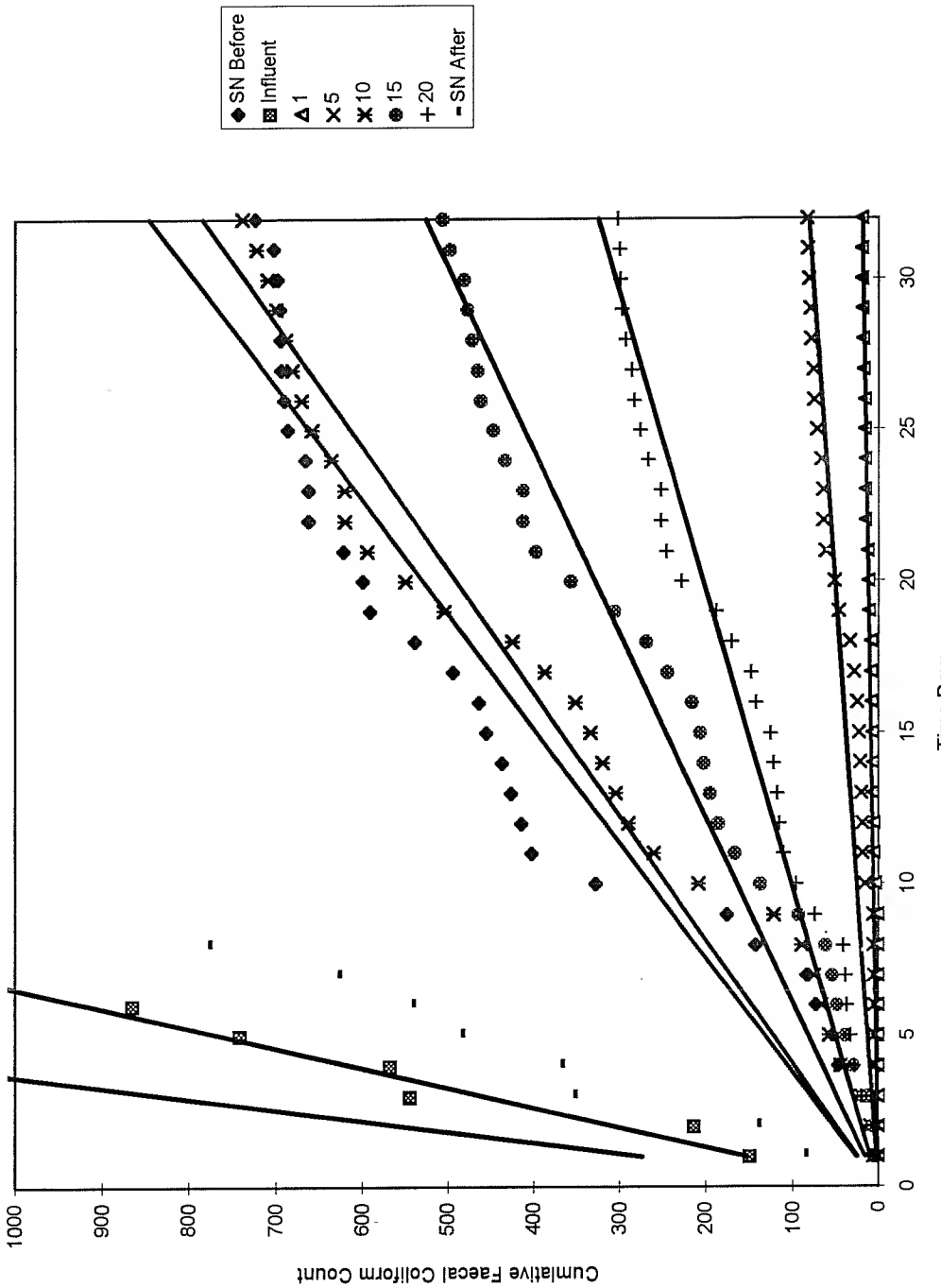

Figure 8.3 Cumulative Faecal Coliform Counts Over Time

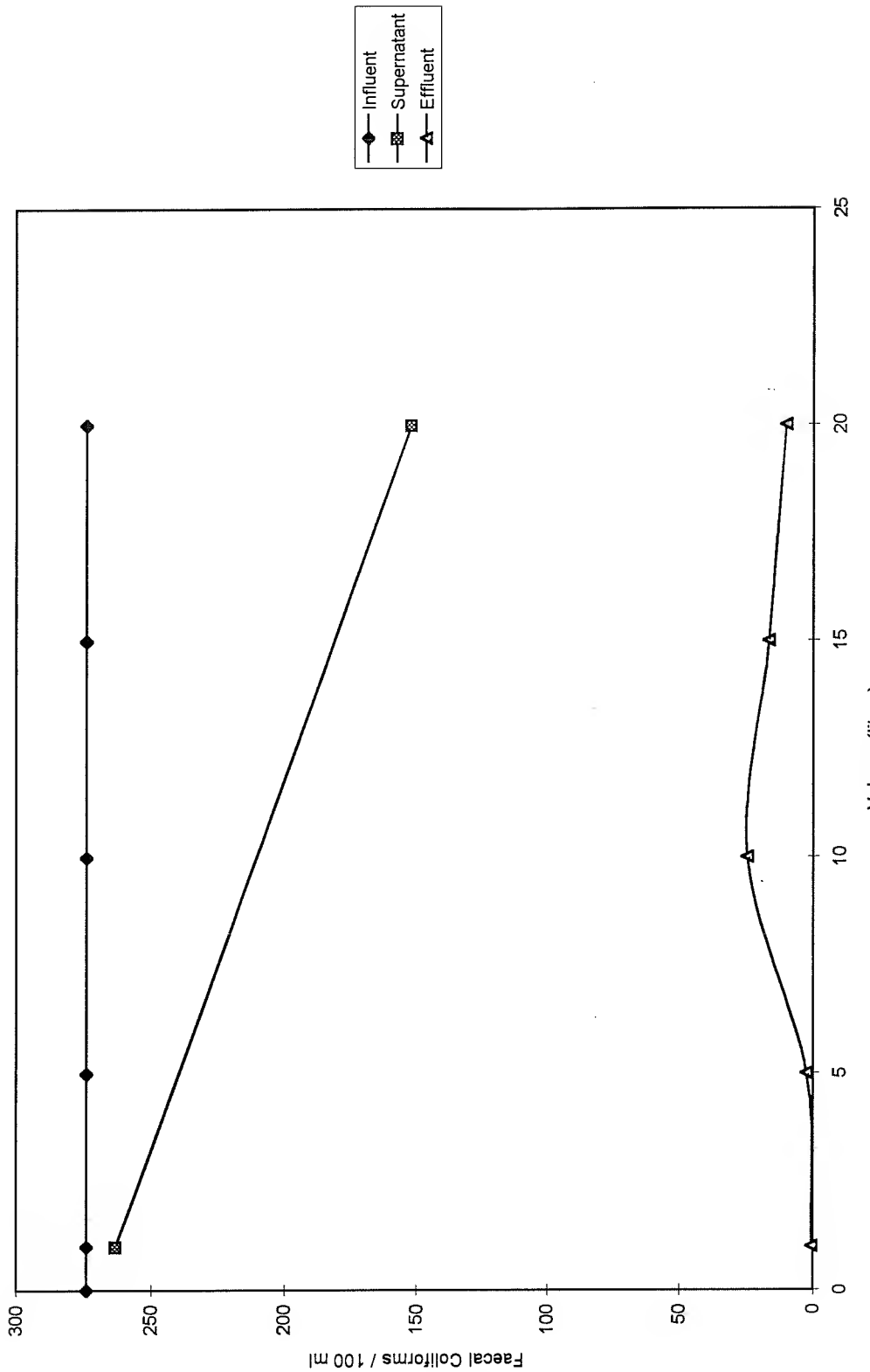

Figure 8.4 Average Faecal Coliform Counts Over a Run

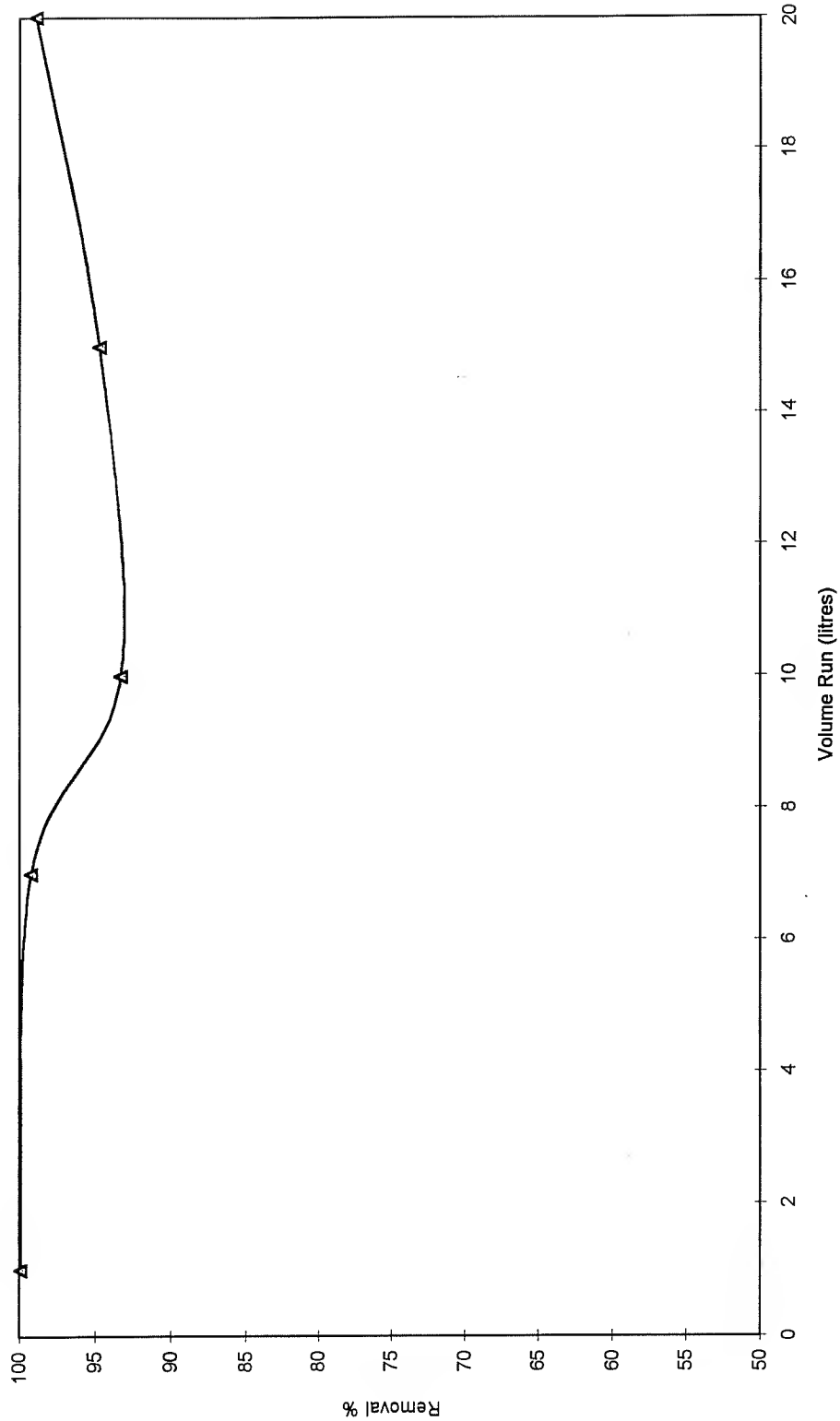

Figure 8.5 Removal of Faecal Coliforms over a Typical Run

shown in Figure 8.4, gave numbers of faecal coliform bacteria in the influent and effluent in an average run. An average run of 25 litres of water contained 68,500 bacteria in the influent and an average effluent of 25 litres contained 2,685.5 bacteria. This gives an overall average removal efficiency for the batch run of 96.1%. The results from this study once again show the effective removal of faecal coliform indicators by intermittently operated slow sand filters.

8.2 Turbidity Test Results

Figure 8.6 is the plot of the different turbidity measurements taken at various sample points throughout the experiment and for the influent and supernatant. It can be seen that the influent has high turbidity fluctuations consistent with a surface water source. There is some loose correlation between influent turbidity and faecal coliform count as turbidity spikes in the influent coincided with weekends as well, however the magnitude of the turbidity spikes did not reflect the magnitude of the faecal coliform spikes. Supernatant turbidities follow the influent turbidities because the only action removing turbidity in the supernatant is settling. The average removal rate of turbidity in the supernatant was 49.7% immediately after the run which gives about 2 hours retention time for settling. The following day before the new influent was added the turbidity of the surpernatant had been reduced by 81.8 % for the averaged values. This high removal rate in the supernatant shows that much of the faecal coliforms in the influent are associated with turbidity causing

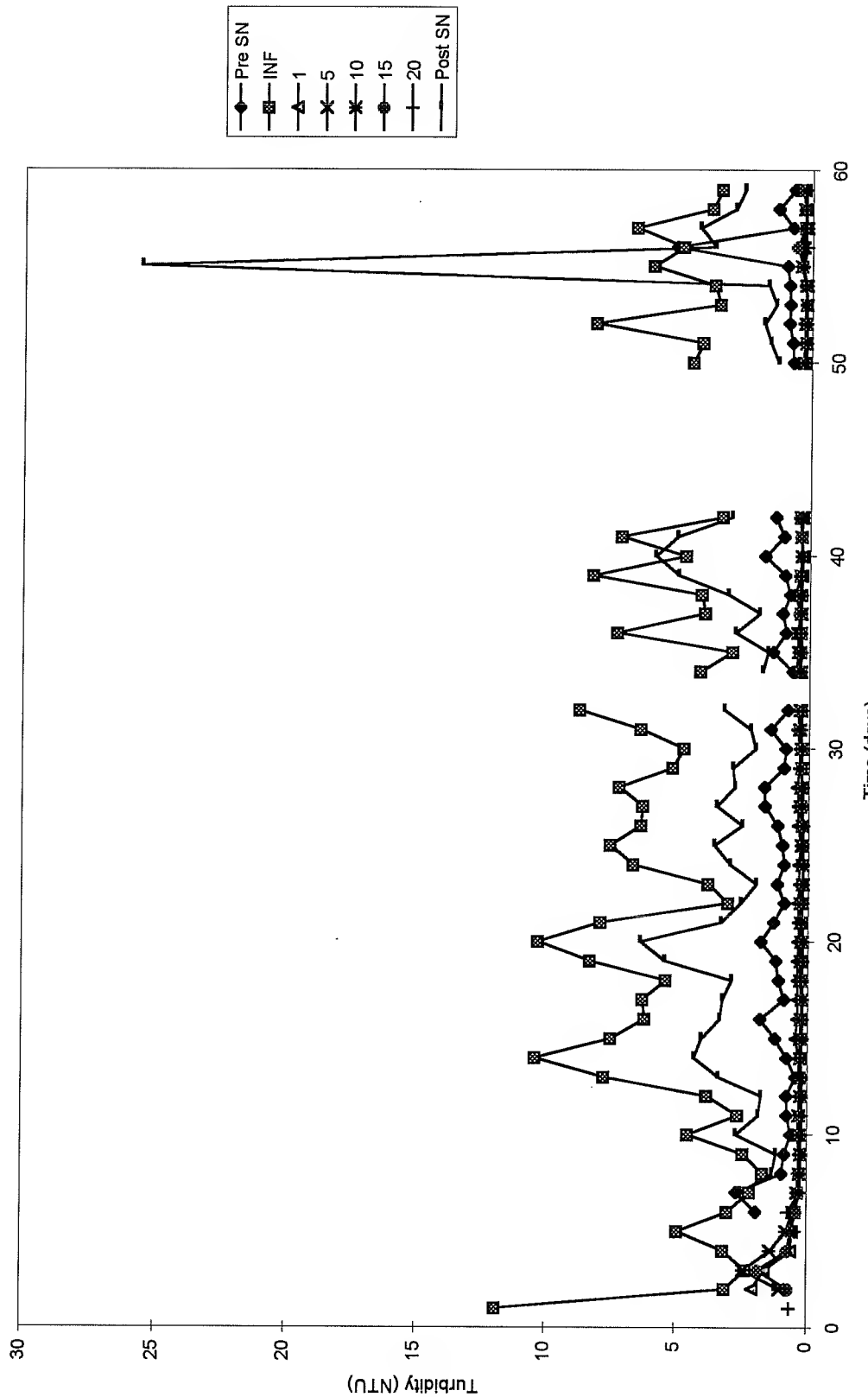

Figure 8.6 Tubidity Changes With Time

particles since the removal rates of faecal coliform are 44.5% after the run and 90.4% after the pause. It is expected that after 24 hours only 4% of particles the size and density of bacteria would be removed, as calculated using stokes equation for laminar settling and assuming the faecal coliform bacteria are not motile. This shows that in the 2 hour length of run the removal of turbidity removes much of the bacteria and that about 89.5% of the bacteria are associated with turbidity. During the pause time many of the bacteria are consumed by predators and natural die off further reduces their numbers until the removal rate for bacteria in the supernatant exceeds the removal rate for turbidity.

Figure 8.7 is a cumulative plot of turbidities. The averaged data for turbidity gave a normal low of 94.1% of to a high of 96.1%. Figure 8.8 is a plot of the turbidity measurements over a run, while figure 8.9 is a plot of the typical percentage turbidity reduction. The weighted average turbidity removal was 95.5%. Turbidities of the effluent reached a low level of between 0.15 to 0.50 NTU after about 7 days and did not vary significantly until the filter was scraped regardless of influent turbidity fluctuations.

8.3 Dissolved Oxygen Test Results

Figure 8.10 shows the variation in dissolved oxygen measurements with time for the different samples tested. The trend for the influent is slightly upward as the ambient

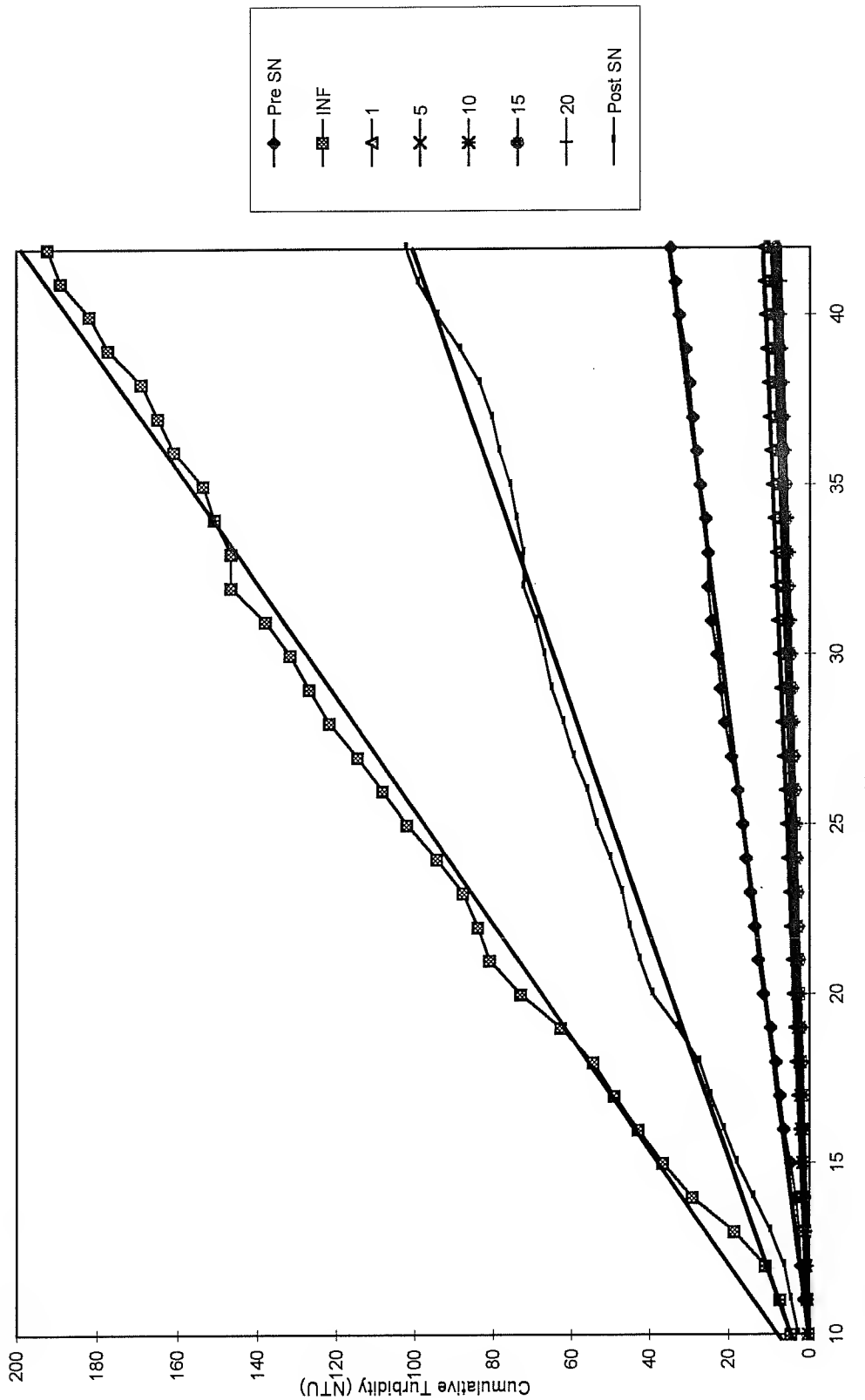

Figure 8.7 Cumulative Turbidities with Time

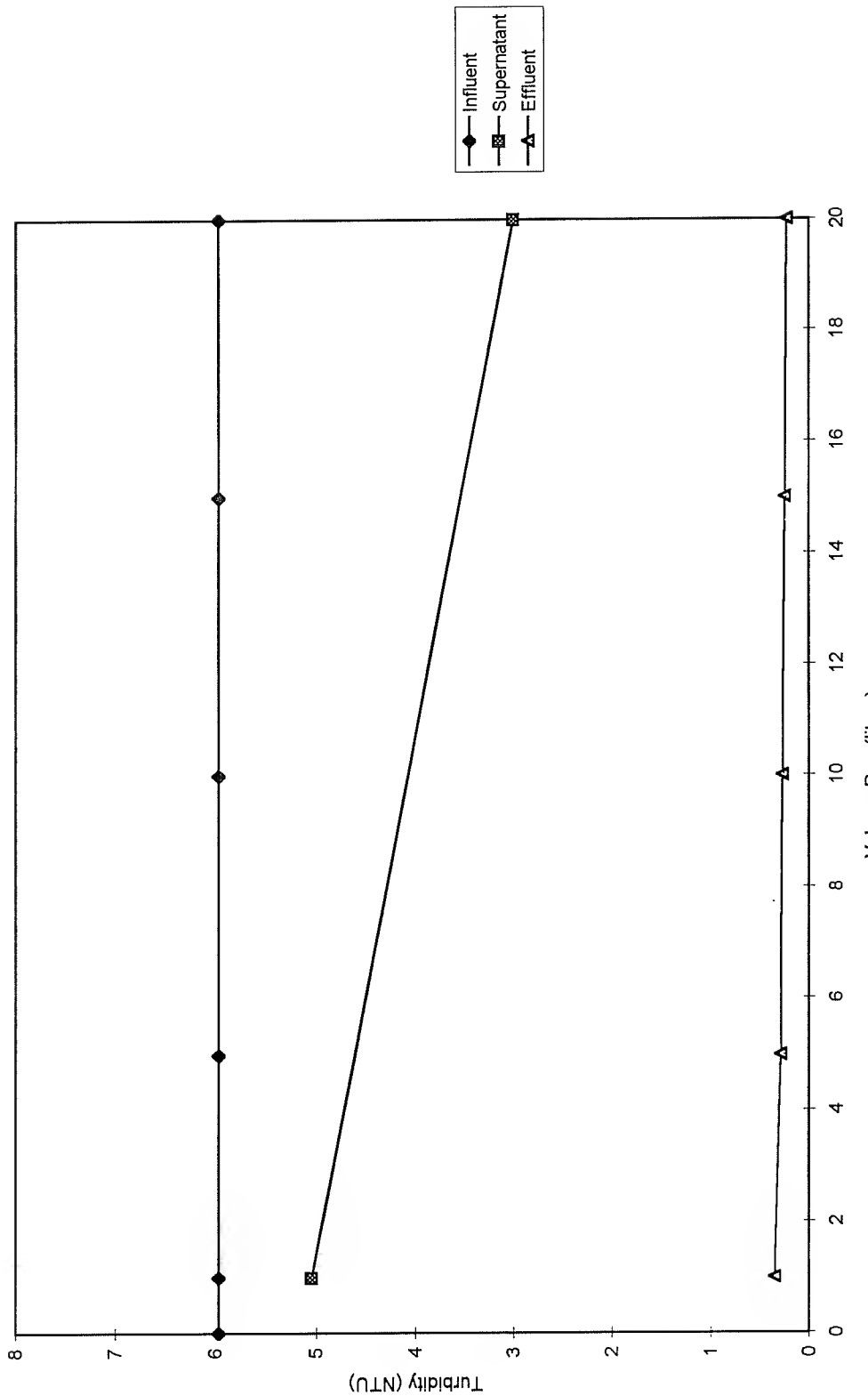

Figure 8.8 Typical Turbidities Over A Run

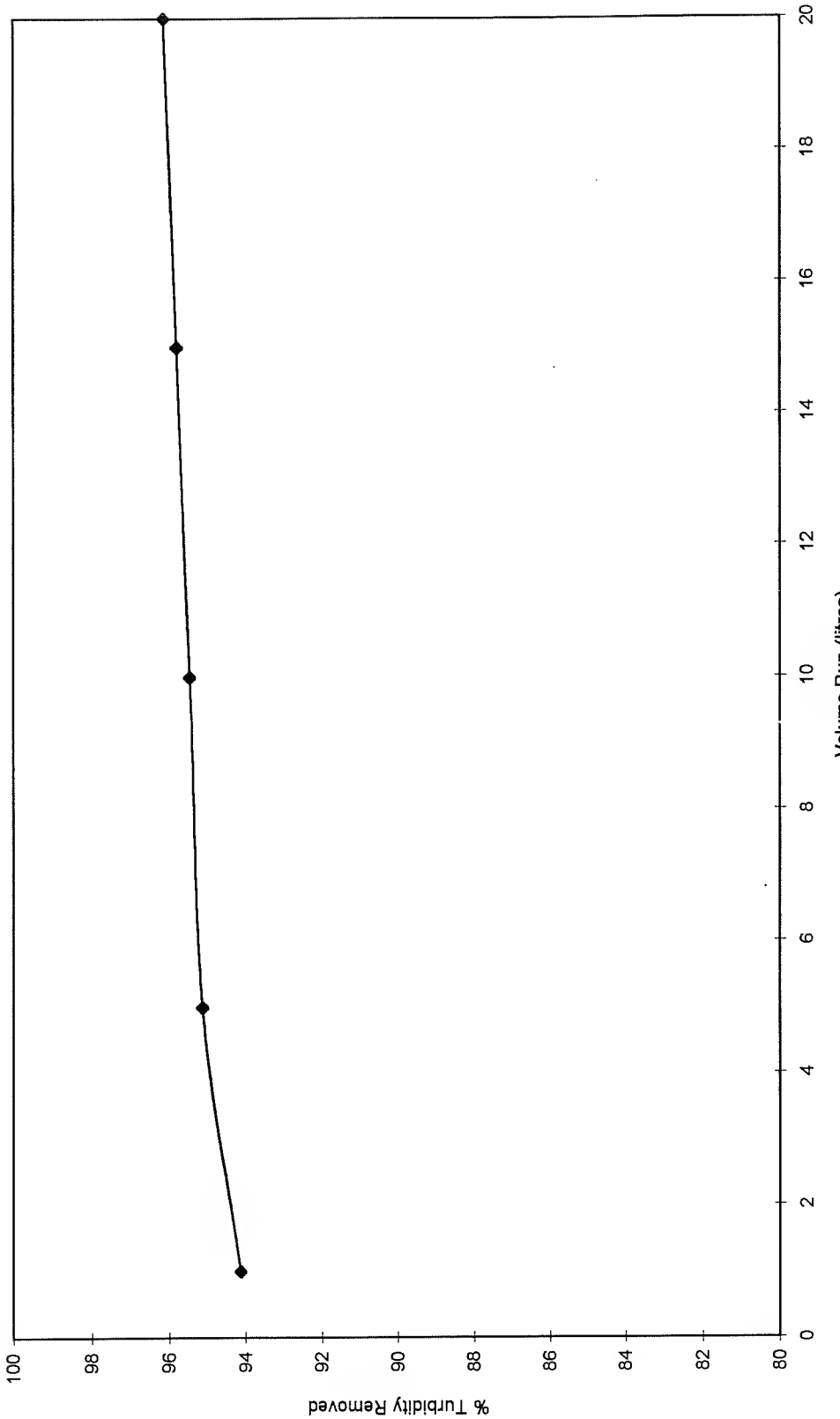

Figure 8.9 Turbidity Removals Over a Typical Run

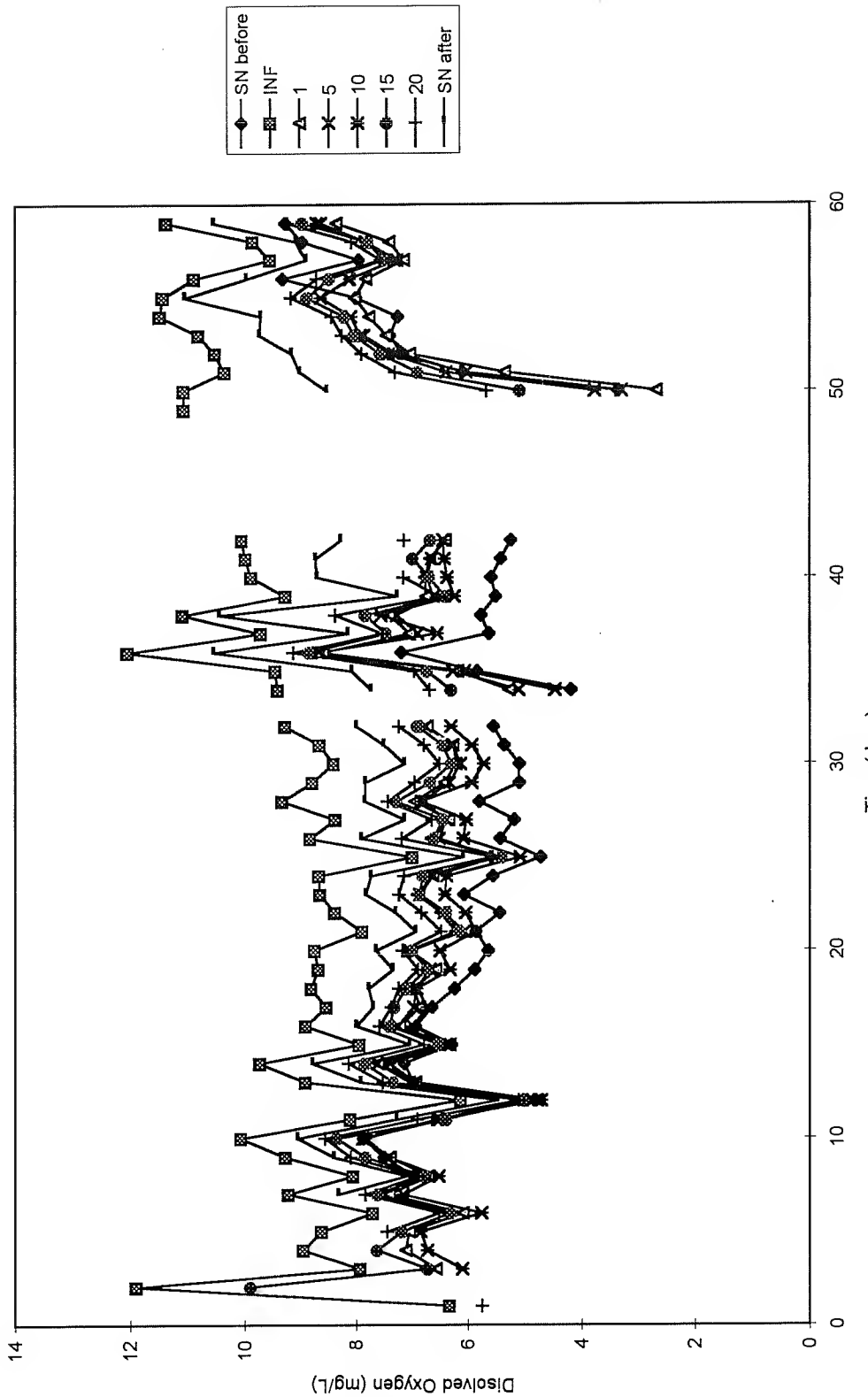

Figure 8.10 Variation of Disolved Oxygen with Time

temperature decreased towards the fall and the dissolved oxygen in the natural water source increased. The gap between the influent and effluent samples increased over time as the biological layer in the filter grew and the demand for oxygen increased. Figure 8.11 more clearly shows this trend. Figure 8.11 is a plot of the oxygen differential between the influent and supernatant samples as the days of operation increased. This figure clearly shows the oxygen demand of the filter increasing over time.

A cumulative plot of oxygen deficit removed the effect of the erratic fluctuations and allowed regression lines to be determined and in turn allowed the calculation of typical oxygen levels. Figure 8.12 is the cumulative plot of oxygen deficit and clearly shows upward curving lines that indicate increasing oxygen demand over time. Again, as with faecal coliform test results, typical oxygen reductions were determined, the difference being that a second order polynomial was fitted to the cumulative plot making the formulas time dependent. The dissolved oxygen levels calculated for day 21 are given in figure 8.13. Figure 8.13 follows a very similar trend as the faecal coliform removals shown in figure 8.4. After noting the similarity between the dip in the dissolved oxygen measurement, faecal coliform removals and the declining flow rate the question becomes which results are the cause and which are the effects.

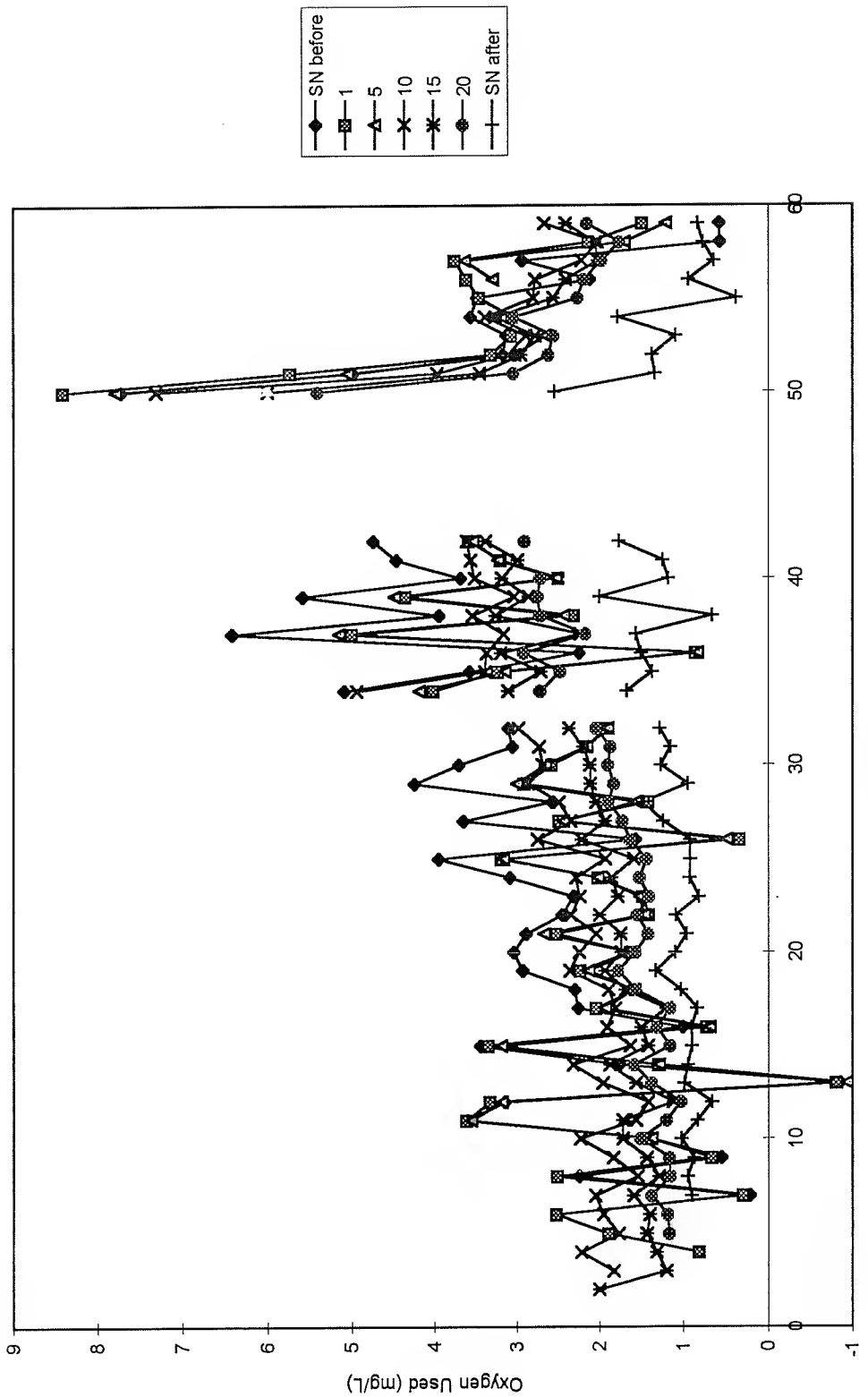

Figure 8.11 Oxygen Use Over Time

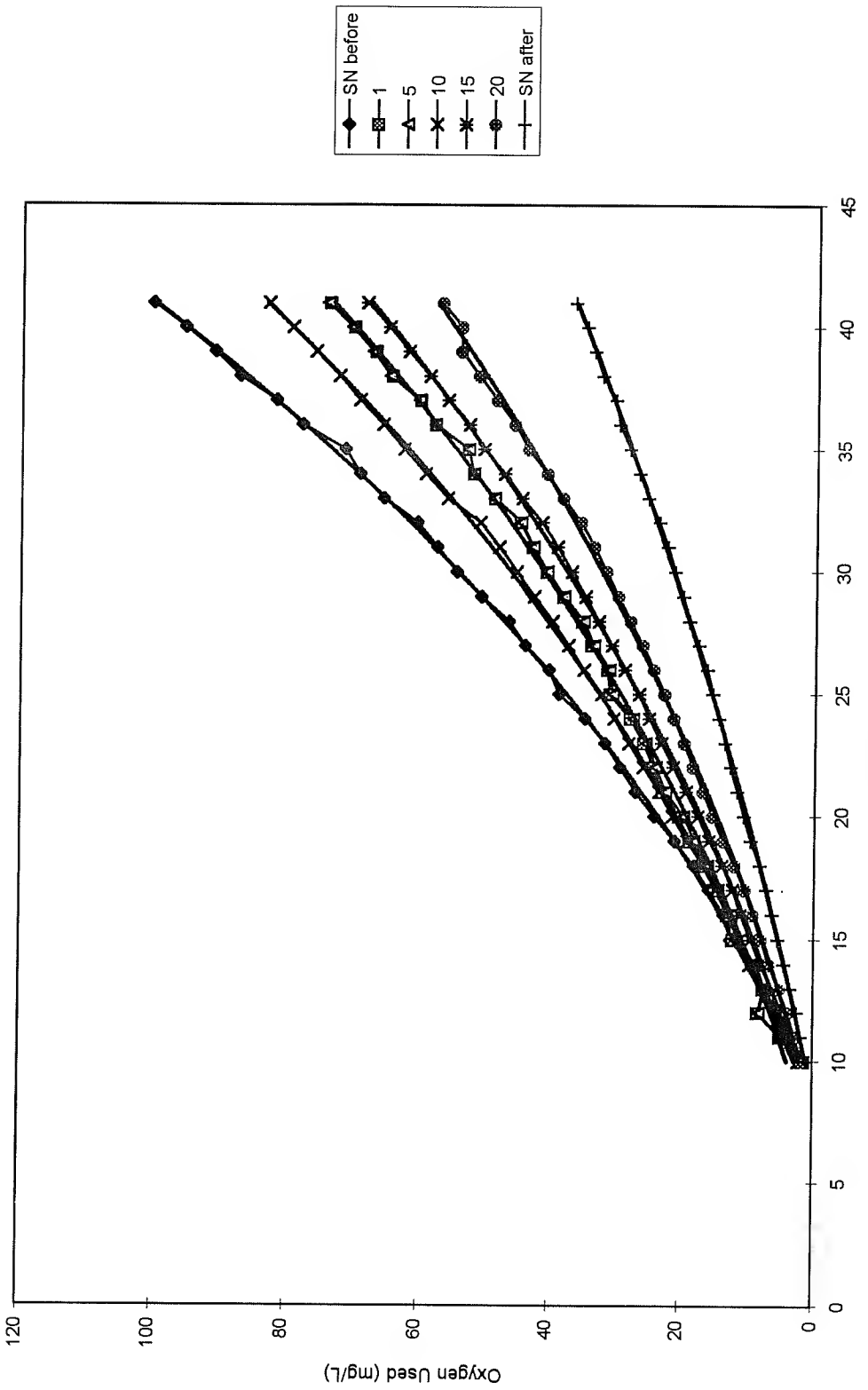

Figure 8.12 Cumulative Oxygen Deficit Over Time

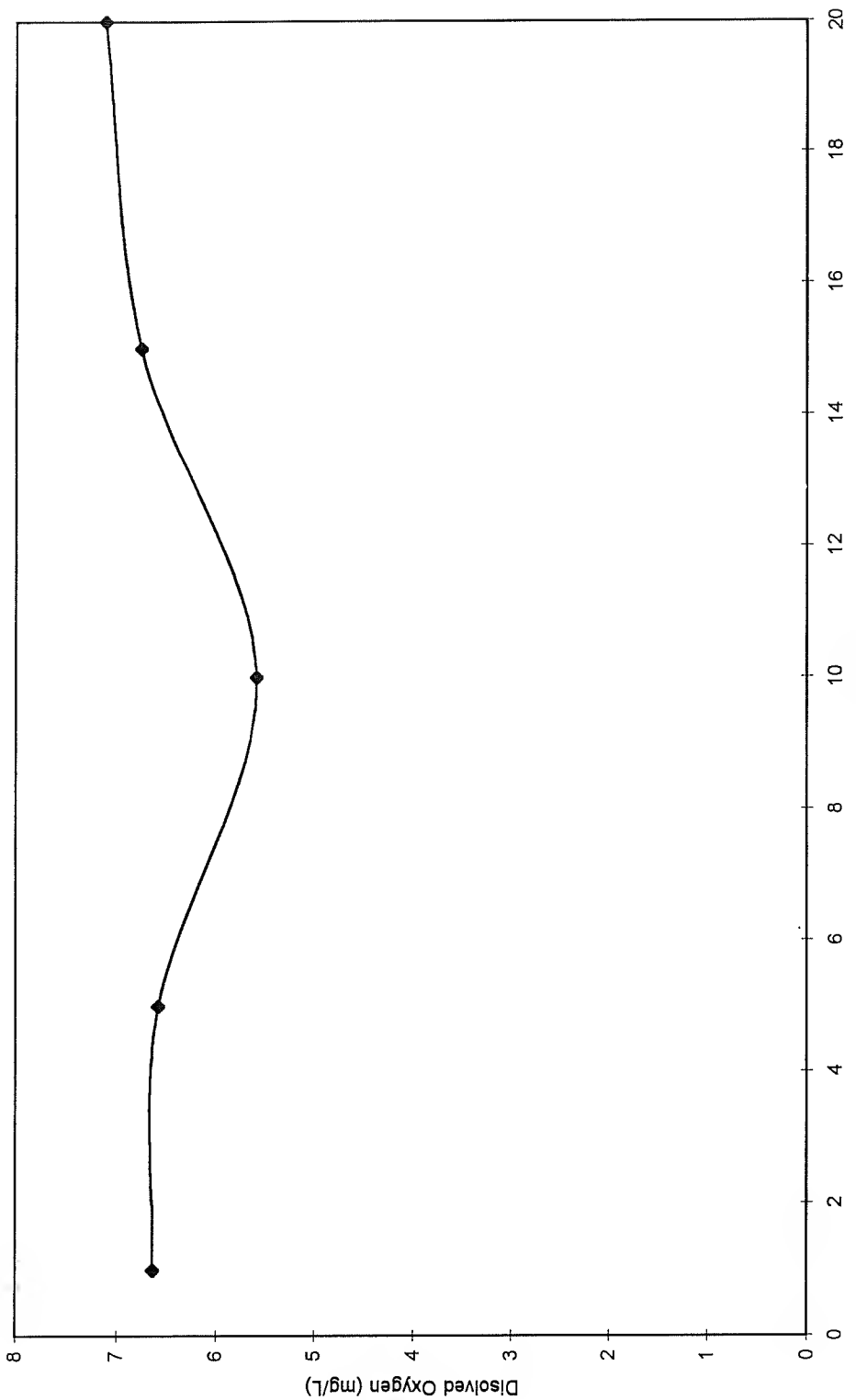

Figure 8.13 Disolved Oxygen Levels for a Typical Run

The oxygen dip occurs at around 10 litres just before the water in the filter sandbed and underdrain is replaced , replacement occurs at 11 litres. After the dip the oxygen level increases towards the concentration of the influent and increases above the oxygen level of the 1 and 5 litre effluent samples. This indicates that little oxygen is used over the actual run period and that the major oxygen changes occur during the pause time. Considering this and knowing the location of the different sample points in the filter during the pause time the oxygen levels within the filter at the end of the pause time can be determined.

Figure 8.14 shows the dissolved oxygen levels through the filter after the pause time. The calculated levels at the water surface is the saturation value for water at 20° Celsius. The oxygen concentration at the sand surface is calculated from the supernatant and saturation oxygen concentration assuming steady state diffusion has been reached throughout the standing water layer. It is assumed that no significant changes occur in oxygen concentrations as the water travels from its position during the rest period until it exits the filter. This of course is not completely true and inaccuracies in the dissolved oxygen measurments allow only generalizations. The location of the sample point during the pause time was calculated using measurements of the actual filter and assuming a sand porosities of 30% and 40%. The figure shows the major oxygen changes occurring in the upper 10 cm of the sandbed over the pause time. This reduction in dissolved oxygen results from the use of the oxygen to metabolise substrates. So we know the depth

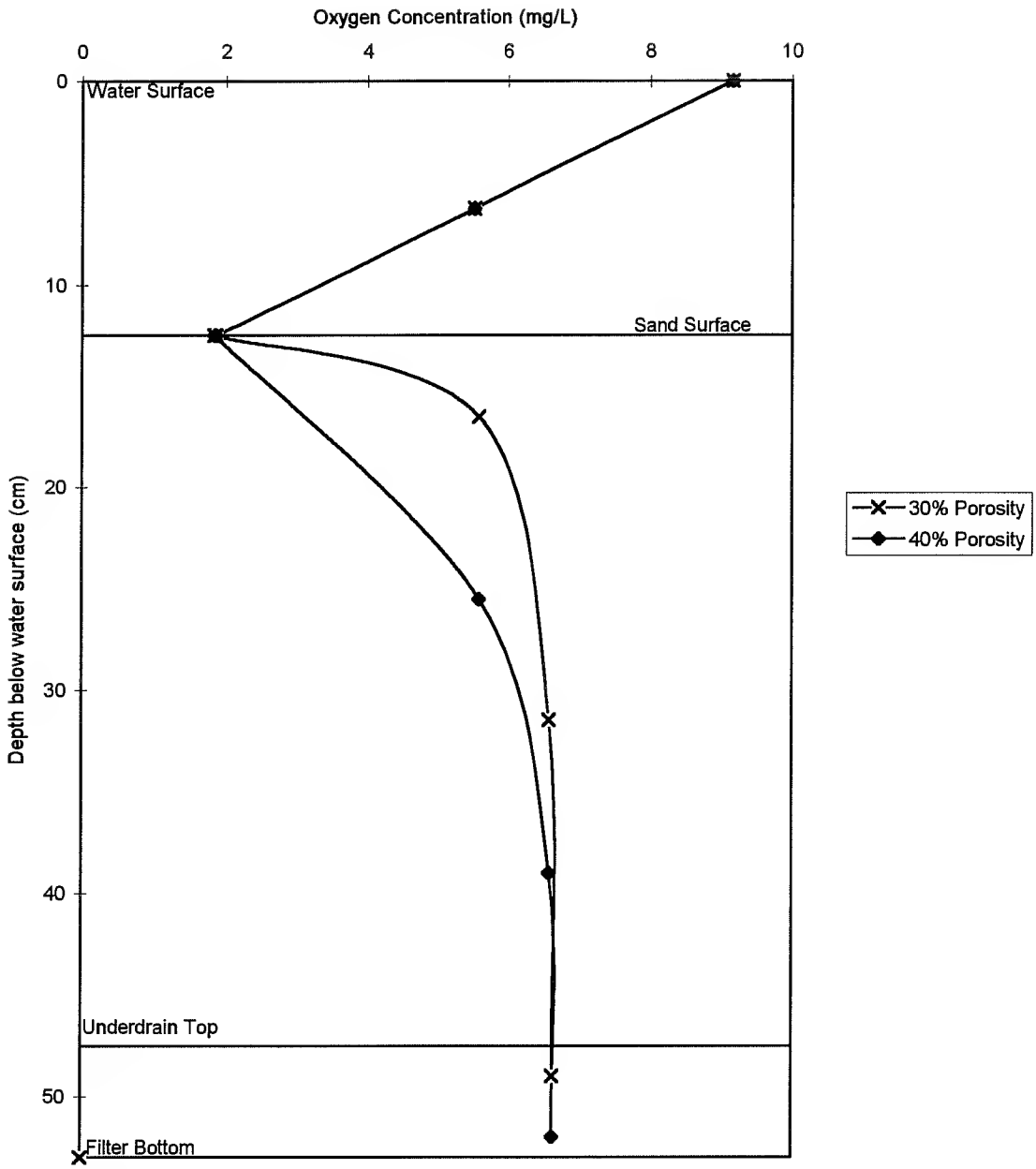

Figure 8.14 Typical Oxygen Concentrations through Filter after Pause Time

of the biologically active zone is around 10 cm. This is consistent with what is expected from the theory developed earlier. Other studies have also noted a decline in removal efficiency associated with the water in the biological layer over a pause time. In addition to the coincidence of the removal dip with the decline in oxygen level. The decline in oxygen and anaerobic condition was thought to be the cause of the poor removal (Paramasivam et al. 1980) however this is not so. This may have been true if anaerobic conditions had been reached in the filter however anearobic conditions do no develop in IOSS filters.

The use of oxygen in the filter is assumed to be part of the purification process and normally a higher use of oxygen would be expected to coincide with a better removal rate since more contaminants would be metabolised. In addition very little oxygen use is associated with water replaced every run, as in the 15 and 20 litre samples, but these have better removal rates than the high oxygen deficit 10 litre sample. The highest removal rates are associated with water that was in the lower sand layers during the pause time and while there was some oxygen deficit showing up in these samples, oxygen levels in these samples are not a lot lower than oxygen levels in the 15 and 20 litre samples. It is know that oxygen in the filters is used to reduce biodegradable contaminants in the filter and these include pathogens. It is also known that the greatest amount of biological oxidation occurs in the sand bed near where the 10 litre sample spends the rest period. However, the greatest micro-biological contamination is found in conjunction with this sample while the other

samples have much better micro-biological quality but have very little oxygen use. This means that the majority of the contaminants must be trapped and metabolised in the upper layers of the sand and contamination remaining after the pause time is washed through the filter with the water contained in the biological layer.

8.4 Hydraulic Conductivities

The hydraulic conductivity data also supports the trapping of contaminants in the upper filter layers and then metabolism of the biodegradable organics over the pause time. Figure 8.15 is the plot of hydraulic conductivity of the filter from the start of the experiment to the first extended pause test. It can been seen that the general trend for all sample points is downward with time. Hydraulic conductivity data are also plotted cumulatively in Figure 8.16 and were regressed against time to give typical trends. As a further check to the accuracy of the regression equations figure 8.17 shows calculated times coresponding to the different sample points plotted against actual values. The hydraulic conductivity over each run decreases with volume run through the filter. A plot of this decline is given for both calculated and measured values in Figure 8.18. After every pause period the hydraulic conductivity, had nearly completely recovered to its initial level of the previous day. This is due to the bio-degradation of organics and pathogens to soluble salts in the filter and openings in the filter skin again being cleared of degradable organics.

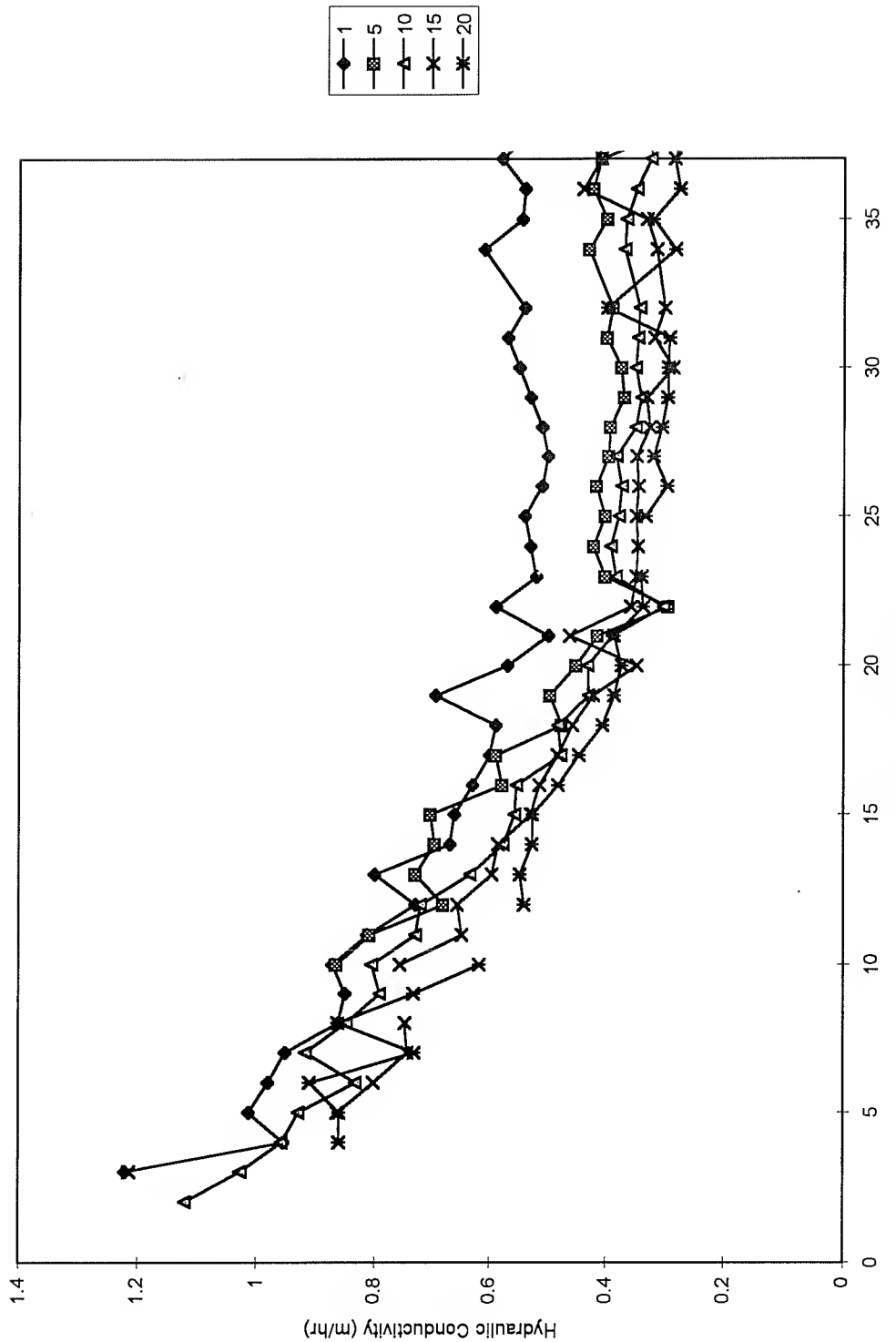

Figure 8.15 Change in Hydraulic Conductivity with Time

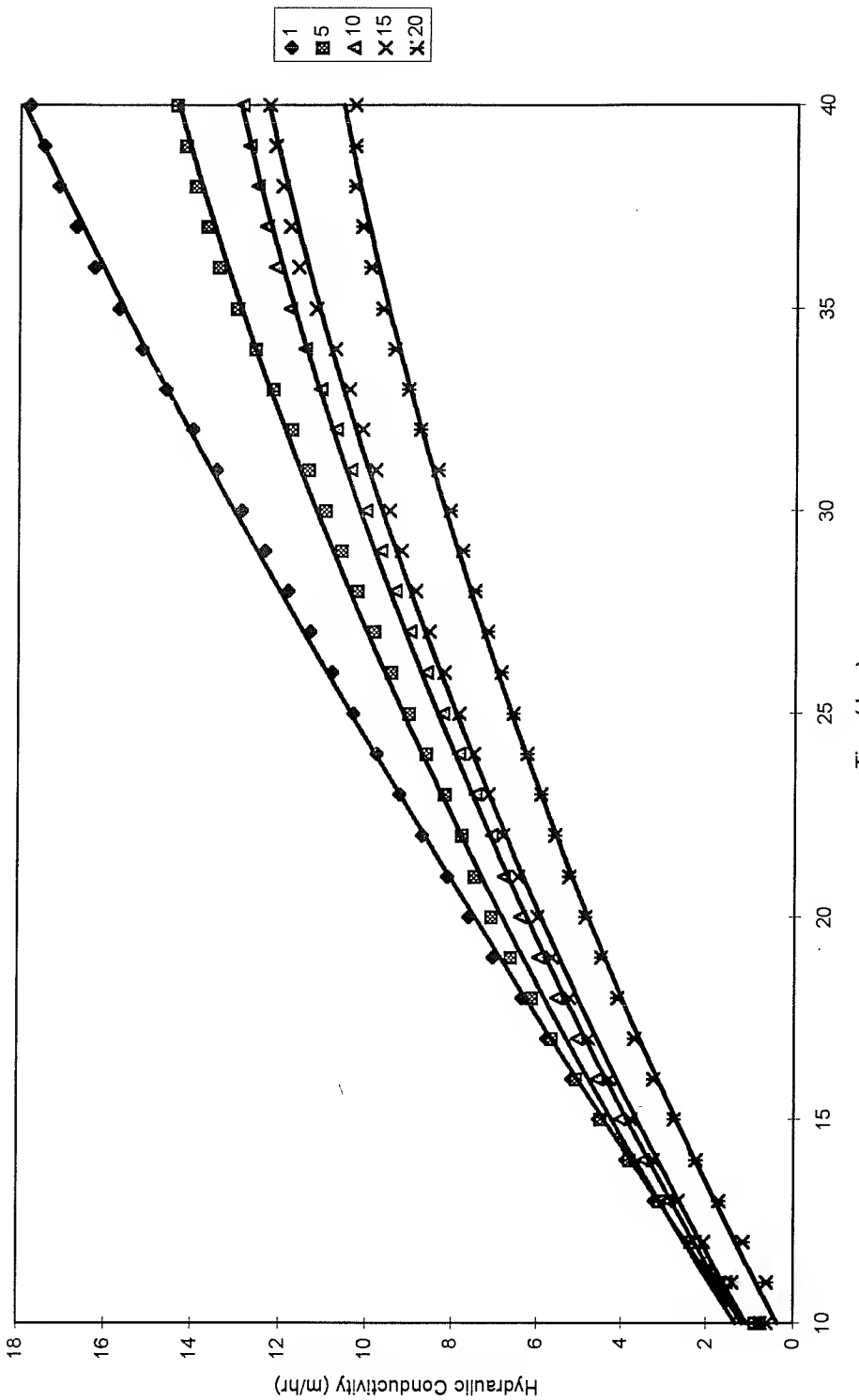

Figure 8.16 Cumulative Hydraulic Conductivity

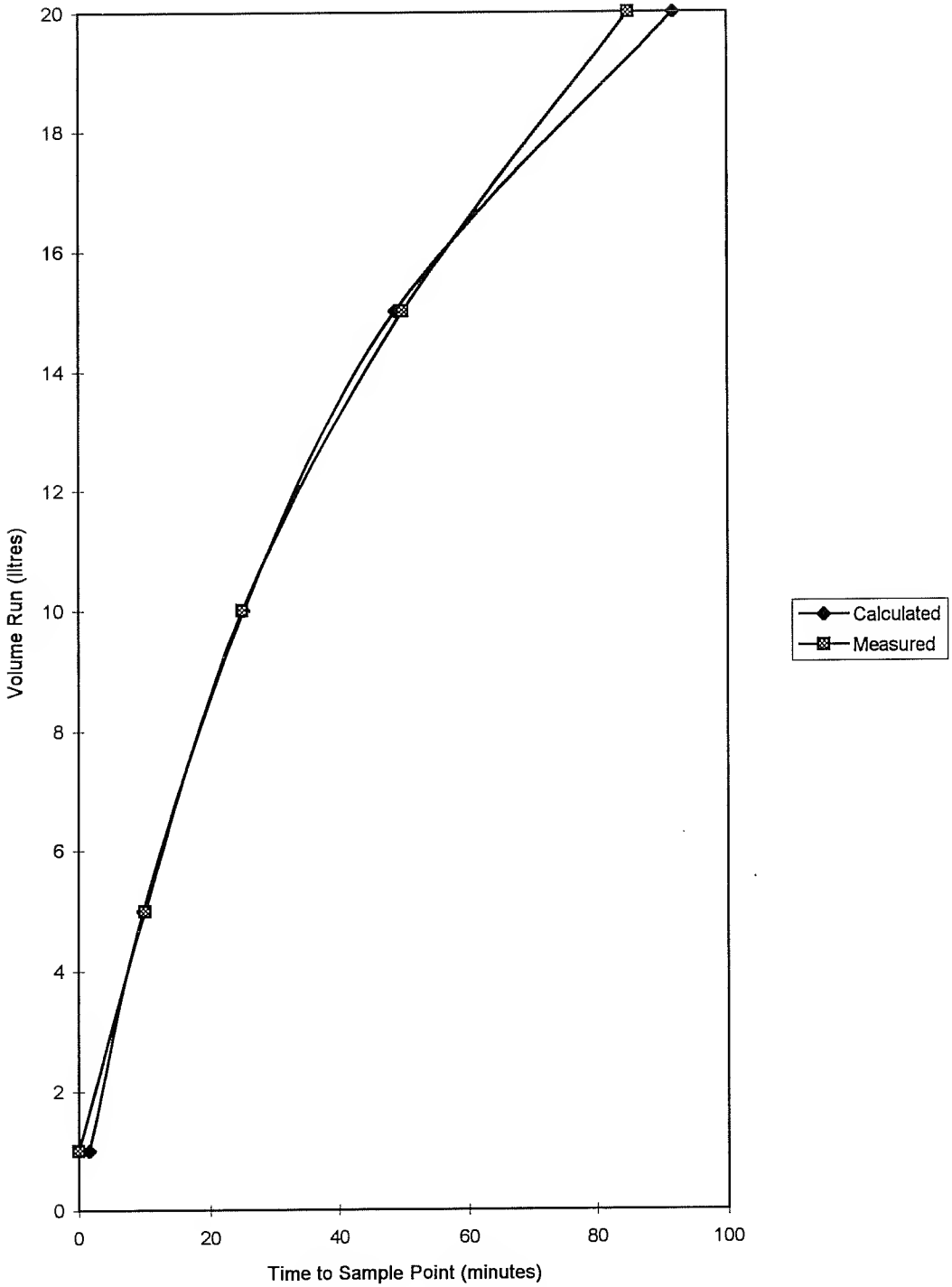

Figure 8.17 Time To Sample Point

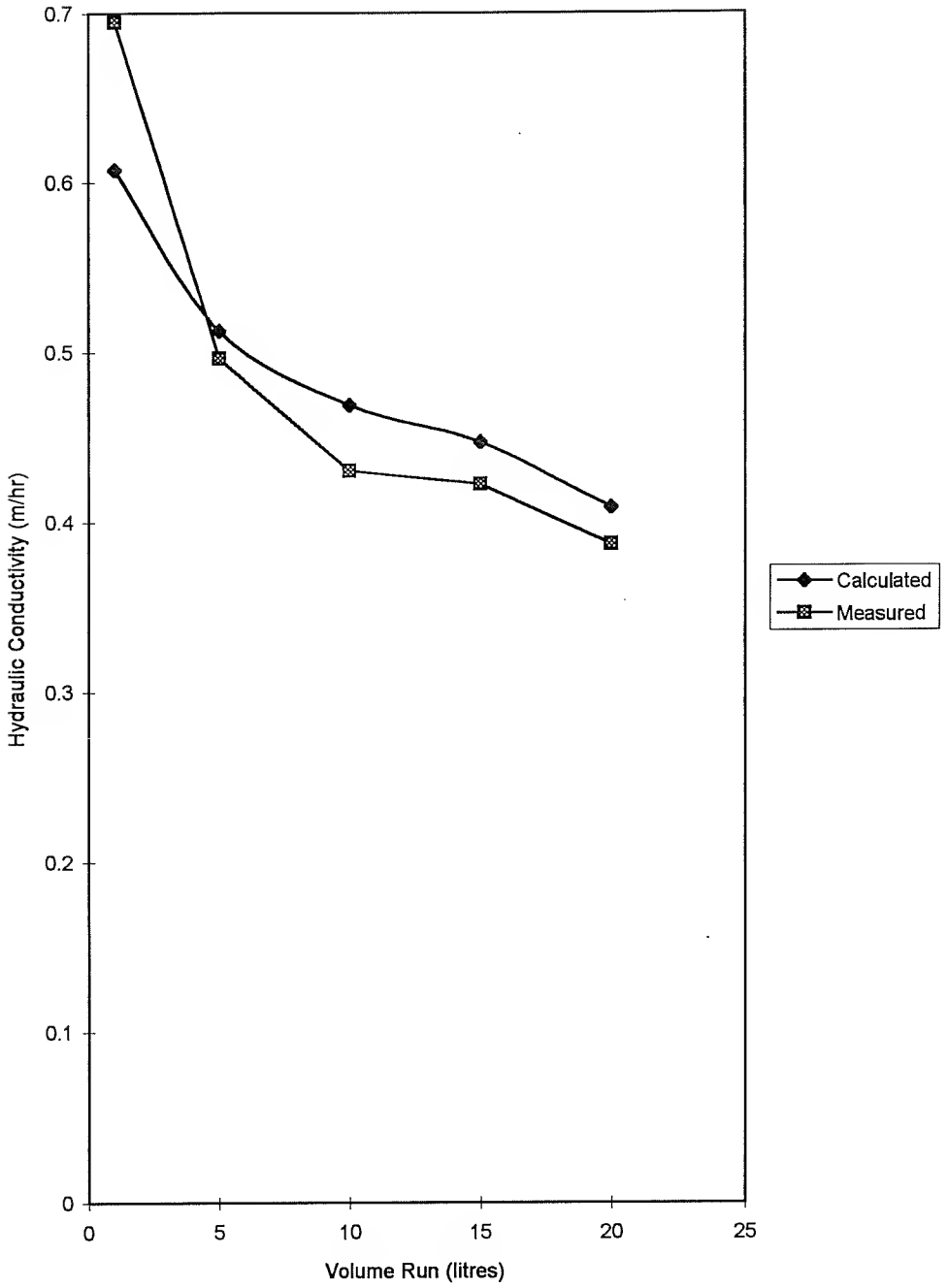

Figure 8.18 Hydraulic Conductivity Over a Run

8.5 Effect of Pause Length

Different lengths of rest period were tried ranging from the normal 18-24 hrs. to 48 hrs to 96 hrs. The longer rest periods showed increasing hydraulic conductivity recovery as well as increased oxygen demand. The effect of changing pause times on hydraulic conductivity is shown in Figure 8.19. Single day data was calculated using the regression formulas determined from Figure 8.16 to give more general results. Hydraulic Conductivities plotted around the 2 day pause test are shown in Figure 8.20. The data for the four day pause is shown in Figure 8.21. Figure 8.19 shows an exponential increase in hydraulic conductivity for the filter as pause length is increased. The graph predicts a pause length of around 1.7 days would cause no average loss in hydraulic conductivity of the filter. The increase in hydraulic conductivity is associated with the decline in oxygen concentrations. Figure 8.22 is a plot of oxygen deficit against hydraulic conductivity recovery for the three lengths of pause time tested. As the pause length is increased the oxygen deficit in the filter approaches a stable constant of a little more than 4.24 mg/L. This is the deficit required to produce a gradient which will allow diffusion across the standing water depth to provide enough oxygen to maintain the activity of the biological layer. Figure 8.23 shows the difference between the oxygen utilisation rate calculated from the theory and the utilisation rate calulated if no oxygen was transfered from the air into the supernatant. The theorectical line shows a much higher utilisation rate which later becomes equal after the filter was scraped on the day 54 of the

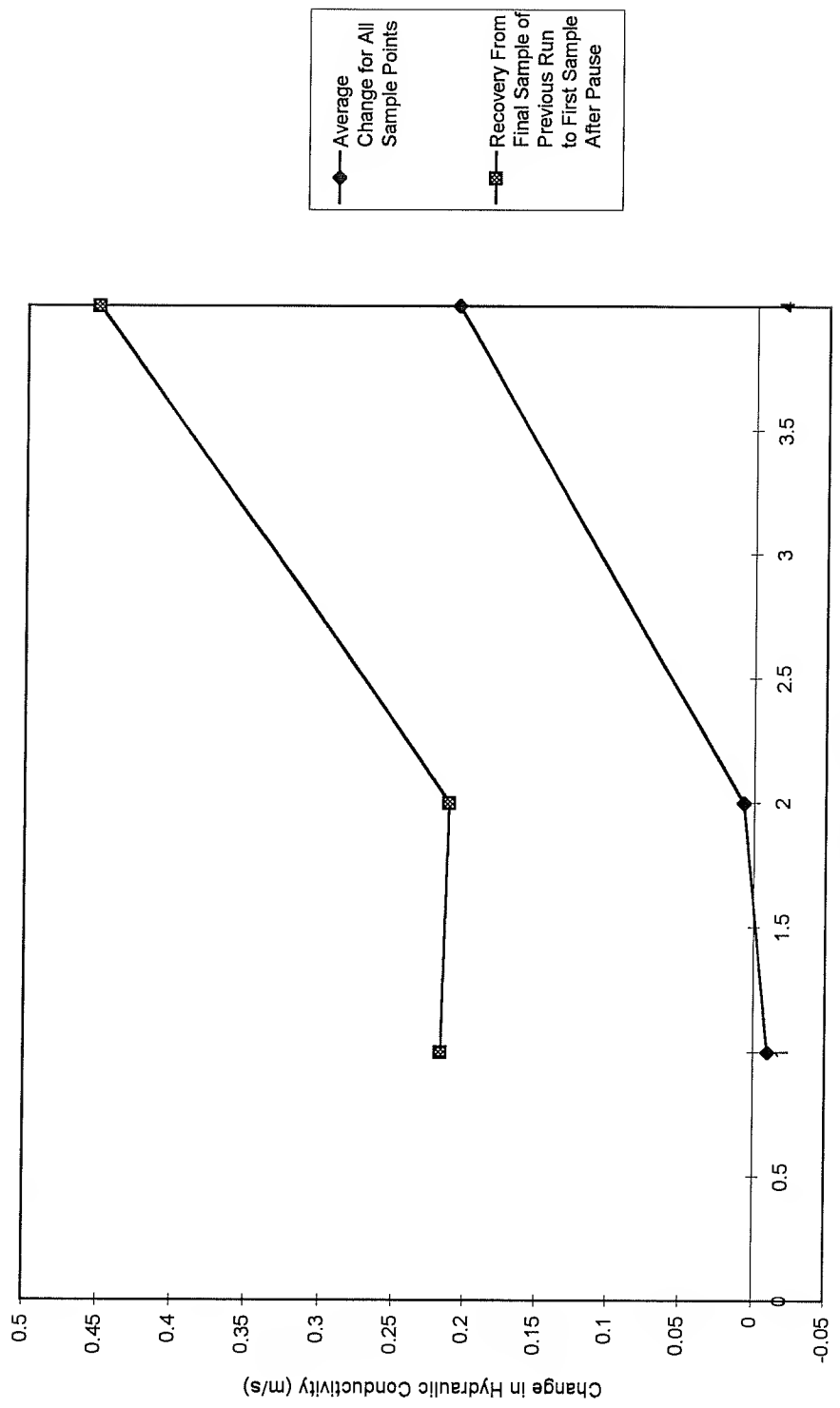

Figure 8.19 Recovery of Hydraulic Conductivity with Increasing Pause Length

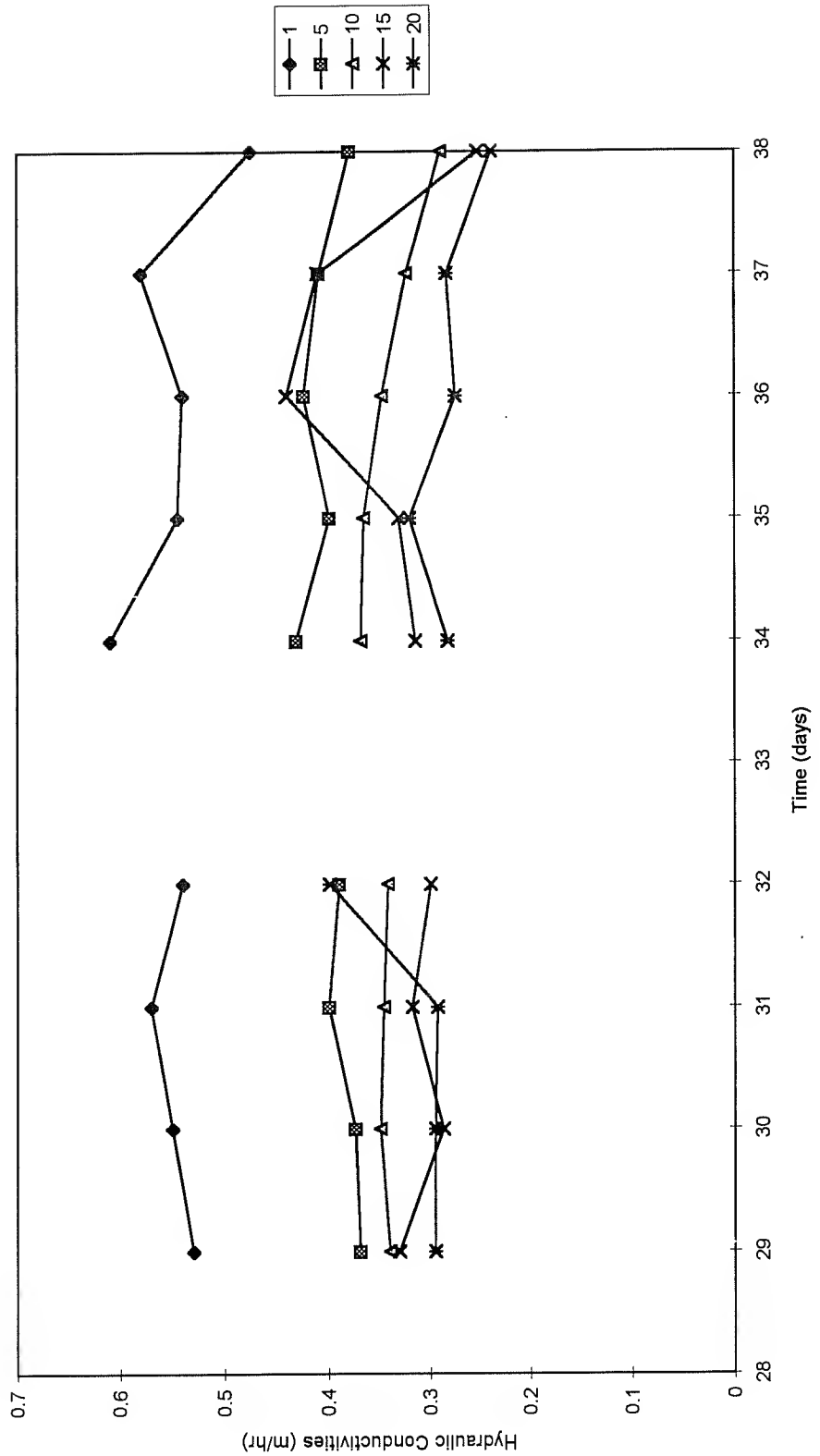

Figure 8.20 Hydraulic Conductivities Around 2 Day Pause Test

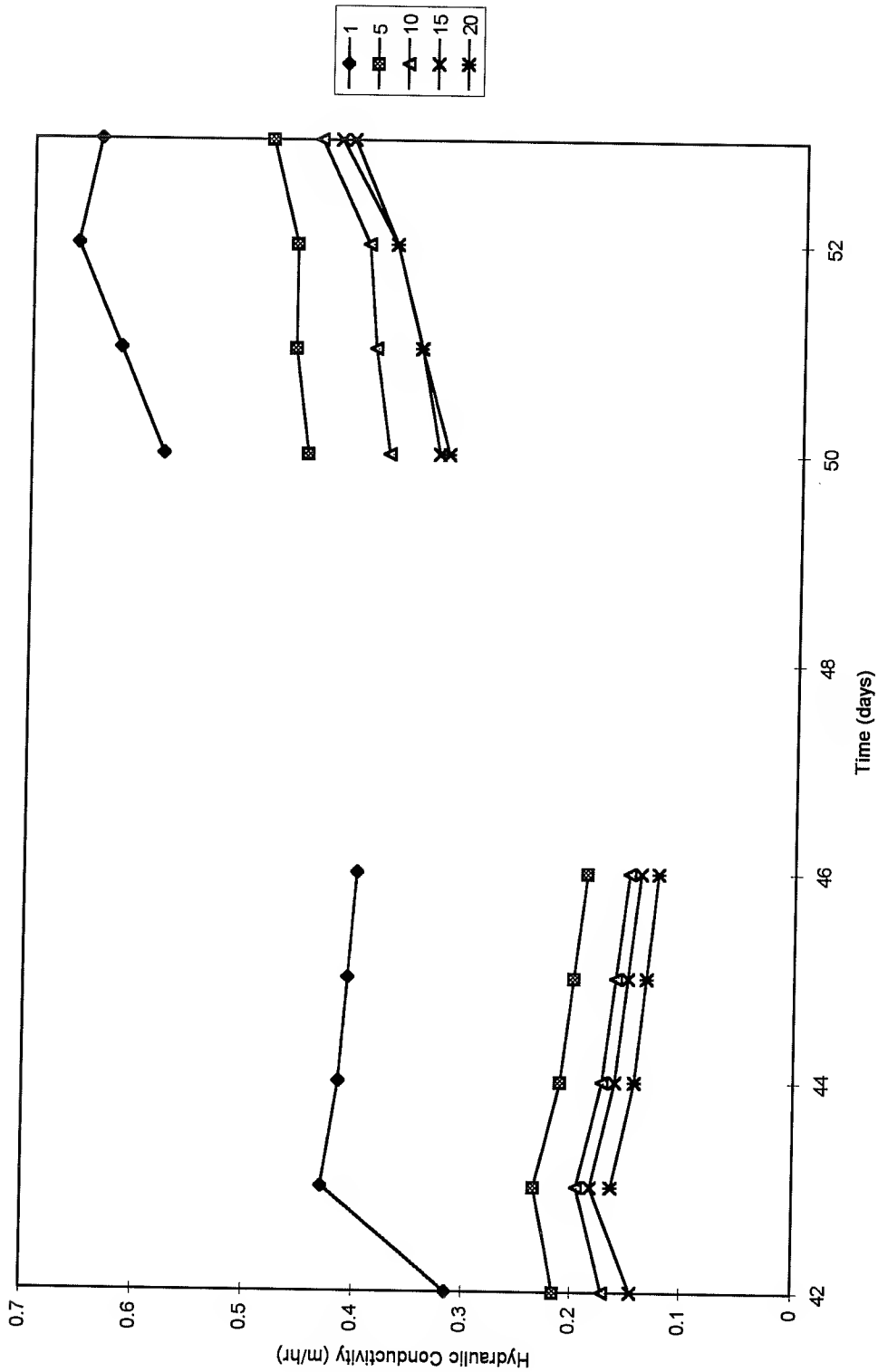

Figure 8.21 Hydraulic Conductivity Recovery After 4 day Pause

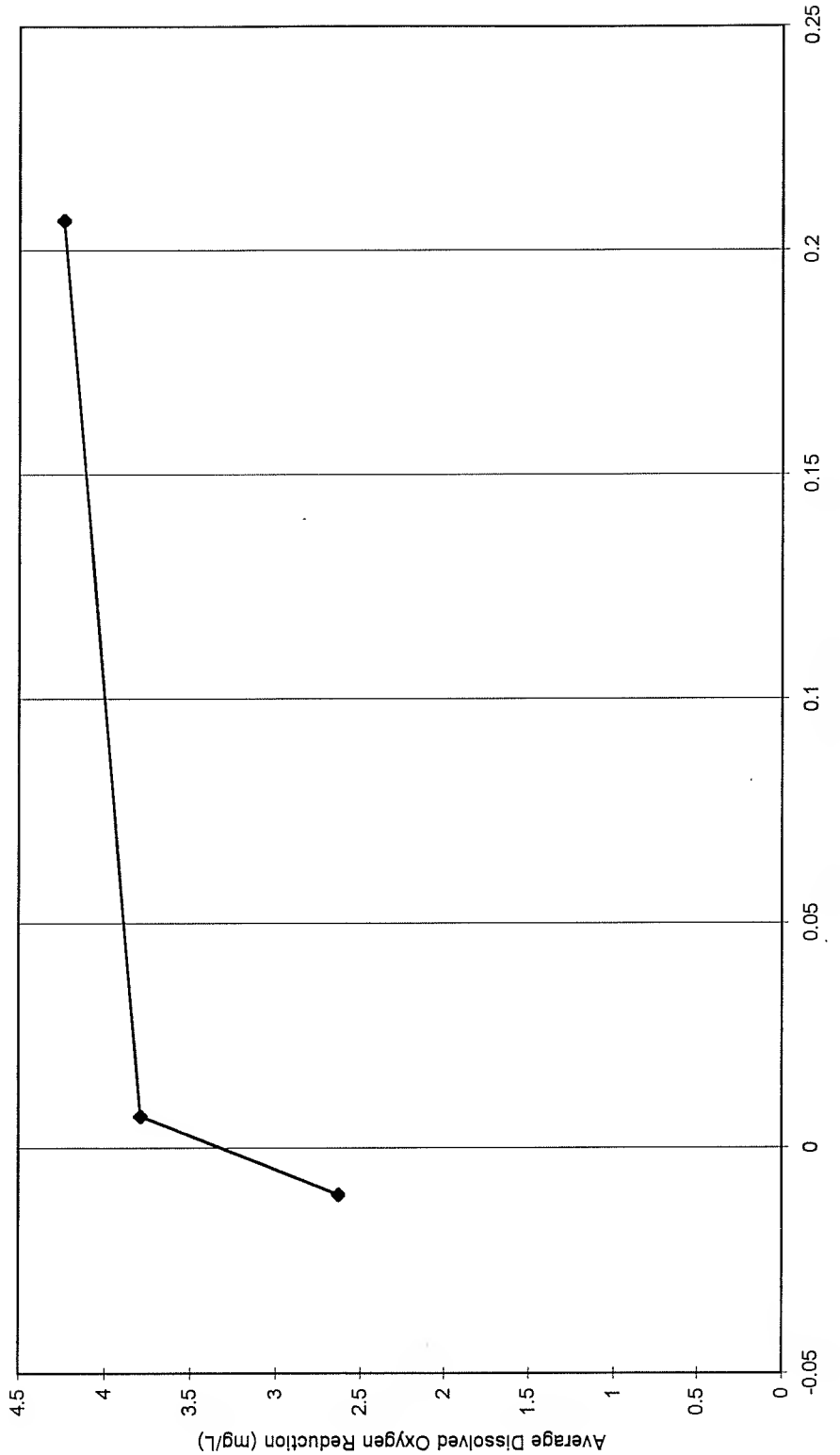

Figure 8.22 Dissolved Oxygen Reduction Versus Hydraulic Conductivity Recovery

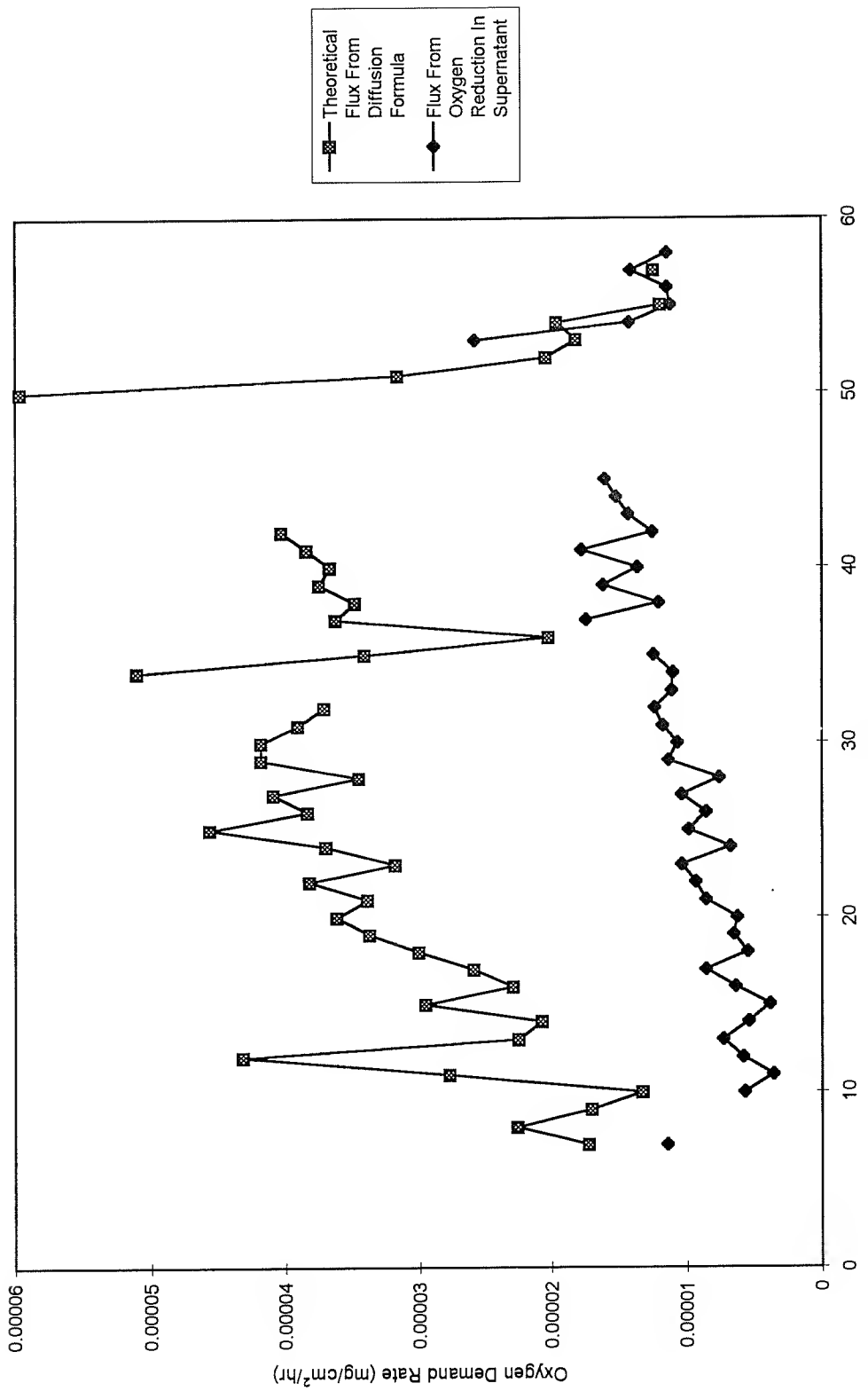

Figure 8.23 Calculated Oxygen Demand Rate

experiment. The apparent increase in oxygen utilisation rate with lengthening pause time is due to the 24 hr time period used in the calculations rather than any significant increase in utilisation rate. During each pause time the hydraulic conductivity recovers to near original levels slightly reduced because of the build up of non-degradable particles and particles which have not been metabolised.

8.6 Scraping Results

Figure 8.24 shows the values of hydraulic conductivity plotted around day 55 when the filter was scraped. This graph shows a marked increase in hydraulic conductivity. The average hydraulic conductivity on day 54 was 0.452 m/hr and after scraping this increased by 0.624 m/hr to 1.08 m/hr after scraping. The after scraping hydraulic conductivity had nearly recovered to the original sand hydraulic conductivity of 1.14 m/hr.

On October 12 the duck pond had been drained so water from the main channel of the bow river was being used during the period around the scraping test. The low level of faecal coliform contamination in the main channel of the Bow River did not allow meaningful interpretation of the faecal coliform results. Although removal rates did recover to 100% two days after scraping.

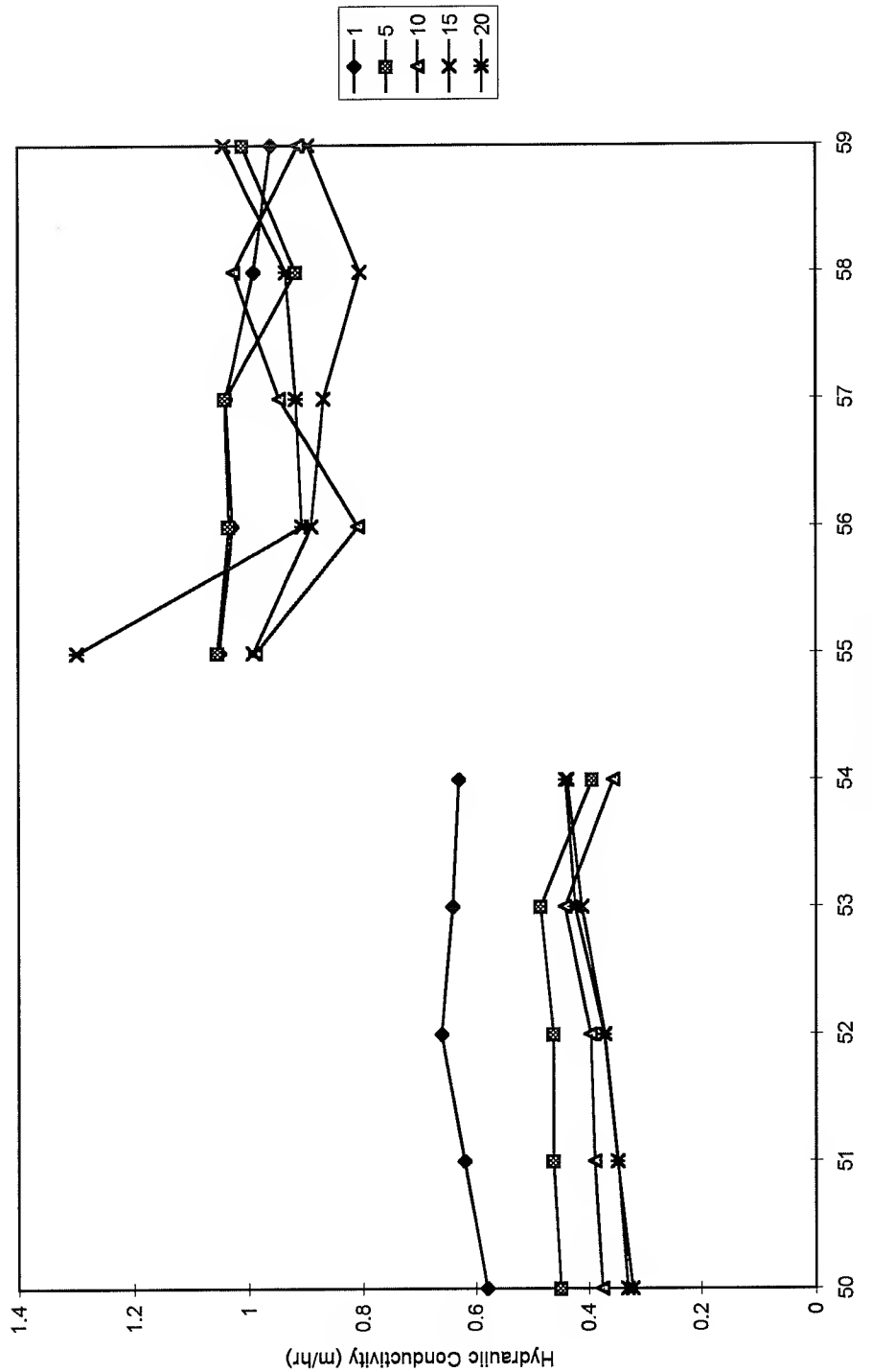

Figure 8.24 Effect of Scraping on Hydraulic Conductivity

8.7 Flow Rate Effects

Once hydraulic conductivities had been calculated for the different sampling points the flow rate of the different sample points as they entered the sand was calculated to determine if there was a correlation between flow rate through the filter and removal rates. After noting the relatively shallow biologically active depth and noting that most of the biological oxidation occurs during the pause time removals during the actual run seemed to be related to flow rate. It is known that the majority of headloss occurs in the upper layers of the sandbed and that this is the area were most of the removals and metabolism of contaminents occur. The flow rate of the different sample points as they entered the sandbed was calculated to give an idea of the effect of flow rate through the biologically active zone and how it effects removal rates. Although mixing occurs with the influent and supernatant when the run is started once the water enters the sand bed the process is assumed to be plug flow. Figure 8.25 shows the relationship between flow rate entering the sandbed and the removal rate for the various sample points. The trend is basically linear with flow rate. Only the 1 litre sample point does not lie along the line. This is due to the low flow rate upon entering the sand bed followed by a long pause in which die off is quite high. It is expected the long pause time significantly effects the faecal coliform removals in the lower sand layers, that is for the 1 and 5 litre samples. The water in these layers at the end of the run are already more than 95% free of bacteria. The low number of bacteria along with very little substrate food make die

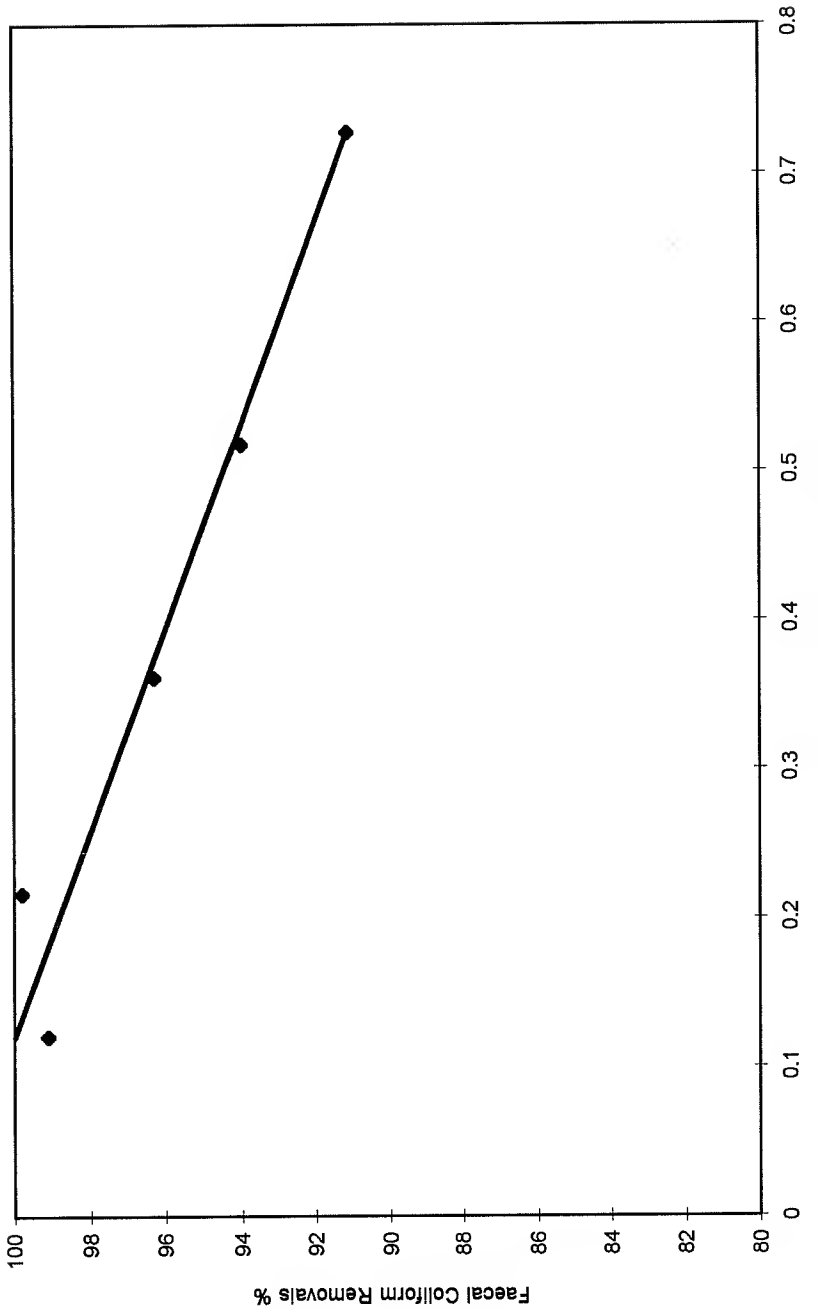

Figure 8.25 Flow Rate Passing Through Filter Skin and Faecal Coliform Removals

off in this area high and are not directly applicable to this graph since both purification and removal mechanisms act on these samples, while the other samples have mainly removal mechanisms acting. We know very little biological oxidation occurs in the lower layers based on the differences between oxygen levels in the 20 litre sample and the 1 and 5 litre samples. The lack of biological oxidation in this region is a result of low concentrations of organisms and low concentrations of substrate.

The poorest removals are associated with the water passing through the biological layer at the highest rate and removal rates increase as flow rate declines. A dip in dissolved oxygen level is also associated with the decline in removal efficiency for faecal coliform bacteria.

Figure 8.26 shows that the above described effect is definitely not a contact time phenomenon. While percent removals of faecal coliforms increases with increasing contact time the dissolved oxygen concentration also increases, indicating that while more material and pathogens are physically removed, less is biologically and chemically reduced. This is expected since the biological reduction of the contaminants will take time while most physical mechanisms operating to remove contaminants from the water into the biological layers surrounding the sand grains are proportional to flow rate.

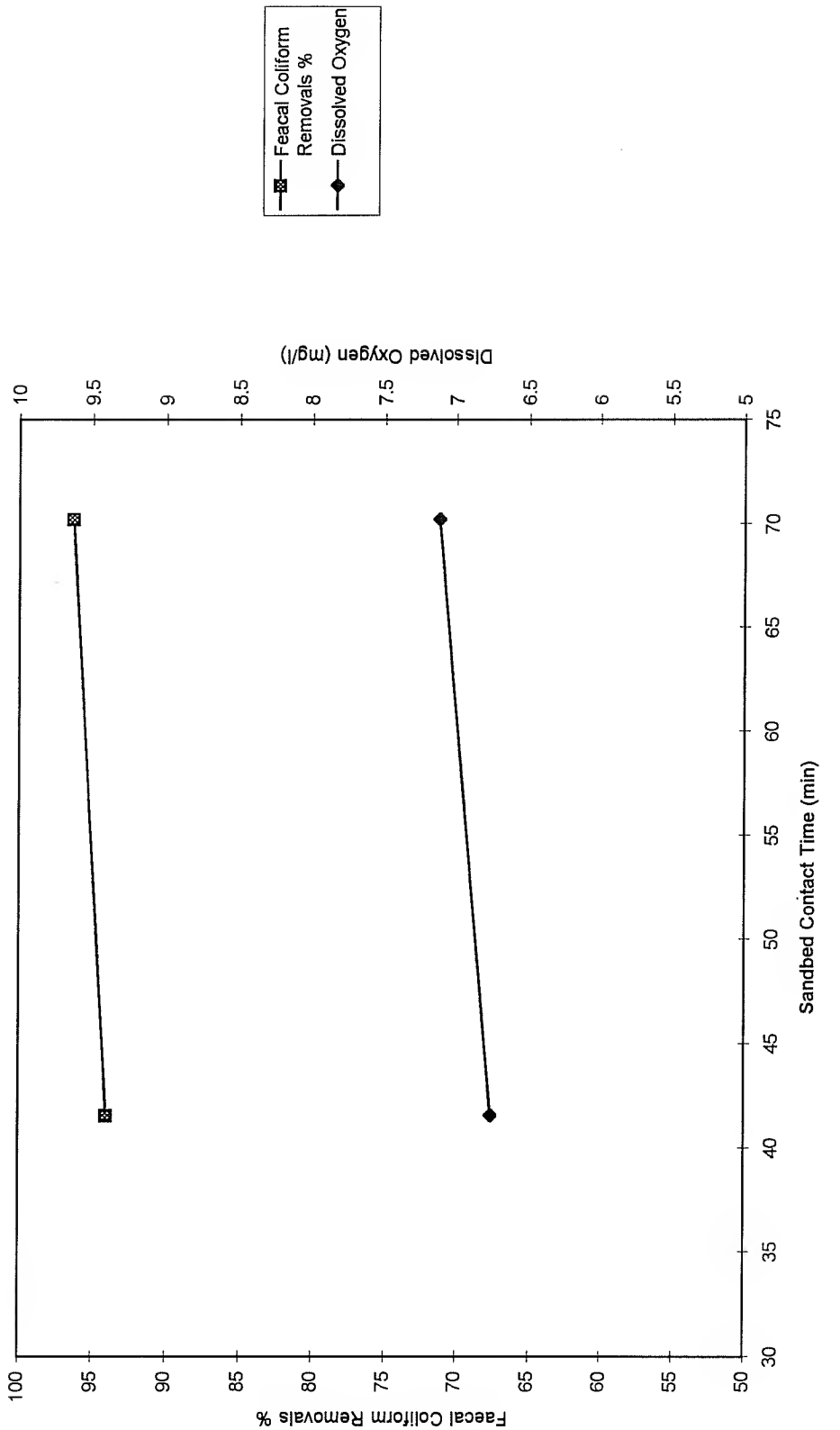

Figure 8.26 Contact Time, Faecal Coliform Removals and Dissolved Oxygen for a Typical Run

8.8 The Carry Over Effect

The days following a high influent coliform count had significantly reduced percent removals of faecal coliforms because the high count was carried over for several days. Two major spikes demonstrate this phenomenon one occurring on day 19 and the other on day 28. The drop off rate seems to take 4 to 5 days before the filters again returns to normal operation. Lower and sometimes negative removals occur at these times because of two factors. One the decline in influent contamination and second the carry over of bacteria from the spike event. Figure 8.27 shows the effluent reaction to the influent spike of 1321 faecal coliform colonies/100ml occurring on day 19.

The carry over or damping effect of faecal coliform bacteria supports the theory that slow sand filtration is mainly a biological process. Purely physical mechanisms would remove a consistent percentage of bacteria regardless of influent concentration. Biological removals, on the other hand, are dependent on the capacity of the life in the filter to capture and consume faecal coliform bacteria. A biological community which has become adapted to conditions where certain amounts of food are available requires time to adapt to a new situation. When an influent spike occurs, the micro-organisms in the filter are unable to consume or destroy all the faecal bacteria or other living contaminants. Remaining bacteria which enter the sand bed survive because there are not enough predators to

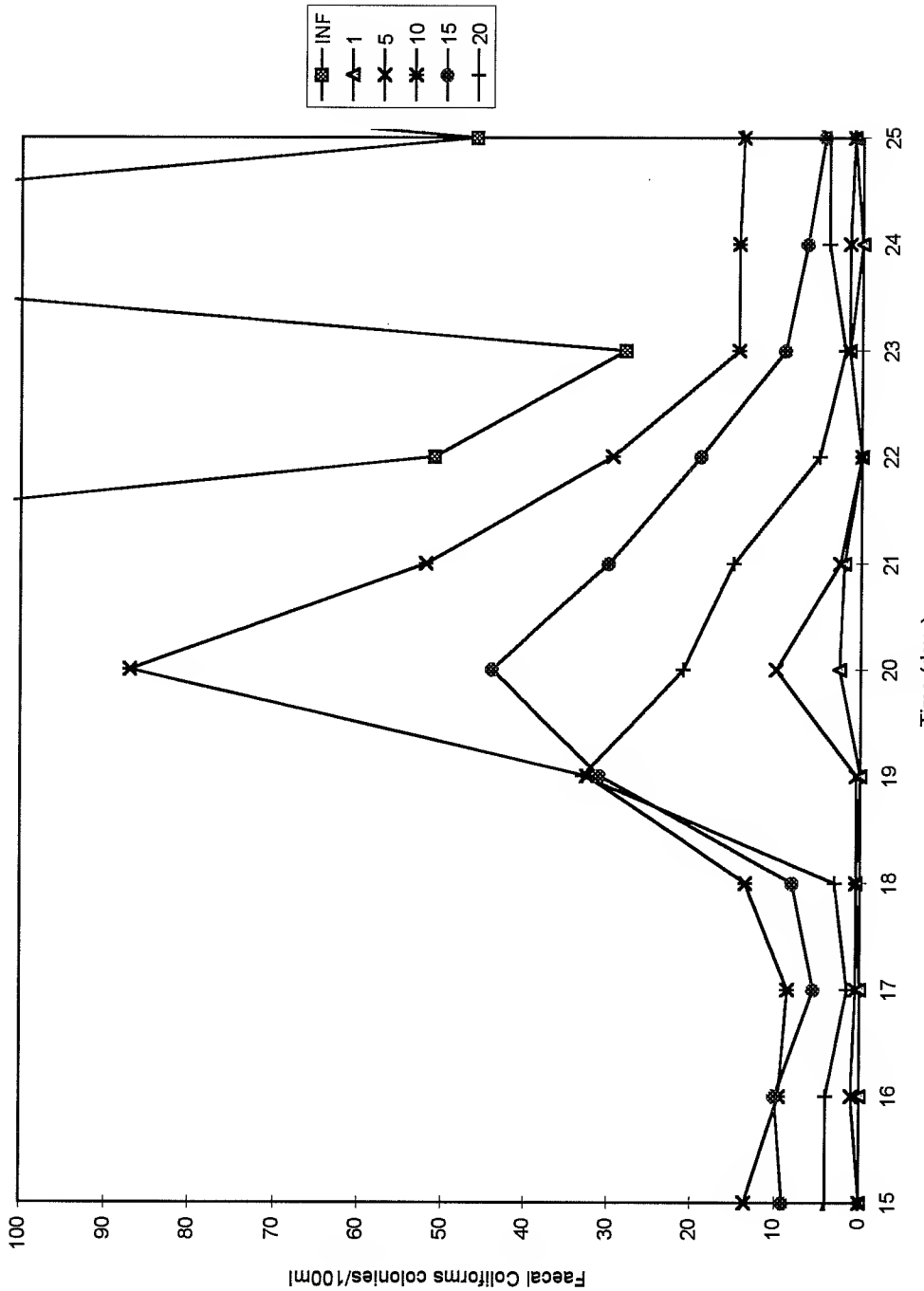

Figure 8.27 Effects of a Faecal Coliform Spike

consume them nor enough ambient life to consume all the substrate which allows them to live. With subsequent passes of water through the bed the surviving bacteria are forced deeper into and finally through the sand bed. With each passing day the ecology of the filter adapts to the new situation by increasing its ability to consume contaminants. In addition as time passes contaminants which have entered the sand bed are consumed and destroyed. This combination of processes results in the spike damping effect shown in the effluent tests of figure 8.27.

The damping or carry over effect causes the spike day data to give better than expected percentage removals while removals from the following day are poorer than expected and can even be negative. Even though the water within the filter was completely replaced each day, bacteria and other contaminants are trapped in the filter skin and upper layers of the sand. During the pause time much of these bacteria and biodegradable contaminants are consumed but not all of them. During the pause time the openings in the filter skin are again opened allowing some of the previously trapped contaminants to be swept through with the initial high flow rate occurring when the filter is again started. A spike event may provide enough biodegradable contaminants so that the filter will not degrade and destroy them completely for several days. This shows up in the effluent as the damped spike lasting several days after the spike events because the new supply of contaminants added to those remaining from the previous day still exceed the normal capacity of

the biological layer. This causes the largest portion of bacteria from a spike to show up in the effluent from the next day.

Most are contamination is destroyed during the pause time however it is estimated more than 95% of the total influent bacteria from the previous runhave been trapped here. The total capacity of the biolayer is used during the entire rest period. This causes a marked reduction in dissolved oxygen and still does not destroy all the bacteria as more time is required to complete the break down and metabolism of the abundant food source. In addition the abundant food at the sand water interface allows the faecal coliforms to reproduce although at very slow rate which is less than the die off rate. It is know that faecal coliform indicators can survive longer than 77 days in surface waters without predation (Dutka and Kwan 1983). When water is again applied to the filter, which is run using a declining head, the initial high flow rate sweeps some of the remaining bacteria out of the biolayer through the expanded pore openings and through the filter with the low oxygen water.

Figure 8.28 shows the same time period as figure 8.27 showing a similar spike in turbidity measurements however the effluent turbidities do not show a carry over effect and remain at their normal low level.

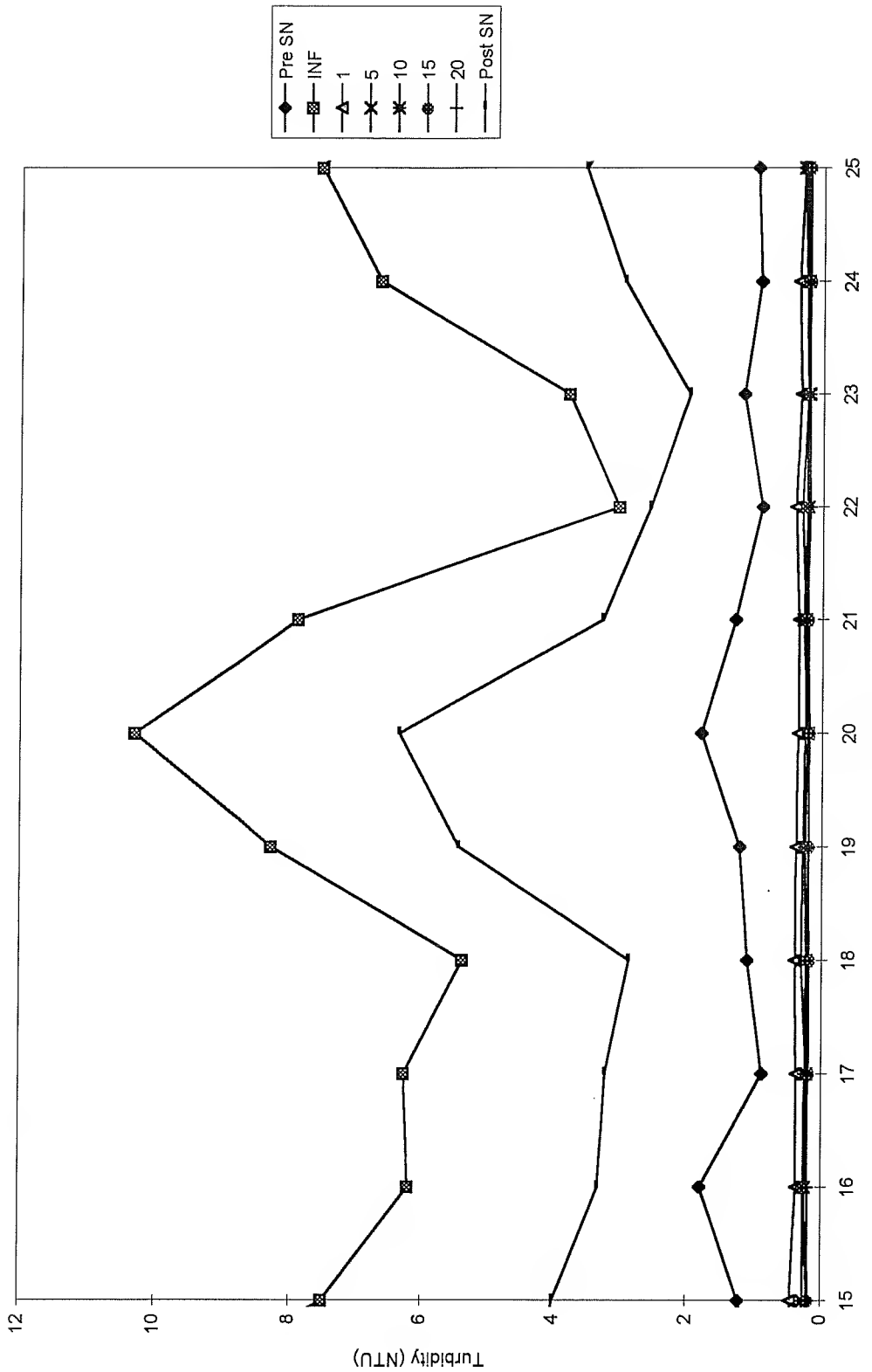

Figure 8.28 Effects of a Faeacal Coliform Spike on Turbities

8.9 Constant Head Test

A constant head test was performed to give more information on the effect of flow rate on the IOSS filter process. However, many other observed phenomenon which had been indicated by shorter runs were also shown in this extended 45 litre run. It was discovered that the hydraulic conductivity of the filter decreased significantly causing the flow rate to decline. It is known that the majority of the head loss in slow sand filters occurs in the top 1 - 2 cm of the sand bed. It is this layer which collects the majority of particles, contaminants and pathogens. This deposition of particles at the sand water interface both reduces the size and total area of pore openings in the filter. Figure 8.29 shows the decline of hydraulic conductivity over the extended run which is very similar to what occur in normal runs. It is of note that the total hydraulic conductivity decline over the extended run is 0.345 m/hr, around one third more than the declines expected in a normal 20 litre run with a hydraulic conductivity decline of 0.254 m/hr. The recoveries however were consistent for a 24 hr pause length, that is 0.280 m/hr compared to the expected of 0.216 m/hr. Figure 8.30 shows the hydraulic conductivities around the constant head test and shows the overall decline in hydraulic conductivities after the 45 litre constant head run.

Unfortunately by the time this test was conducted the regularly used water source, the duck pond, had been drained and the relatively contamination free main channel of the Bow River was being used for this test. This meant that the faecal coliform

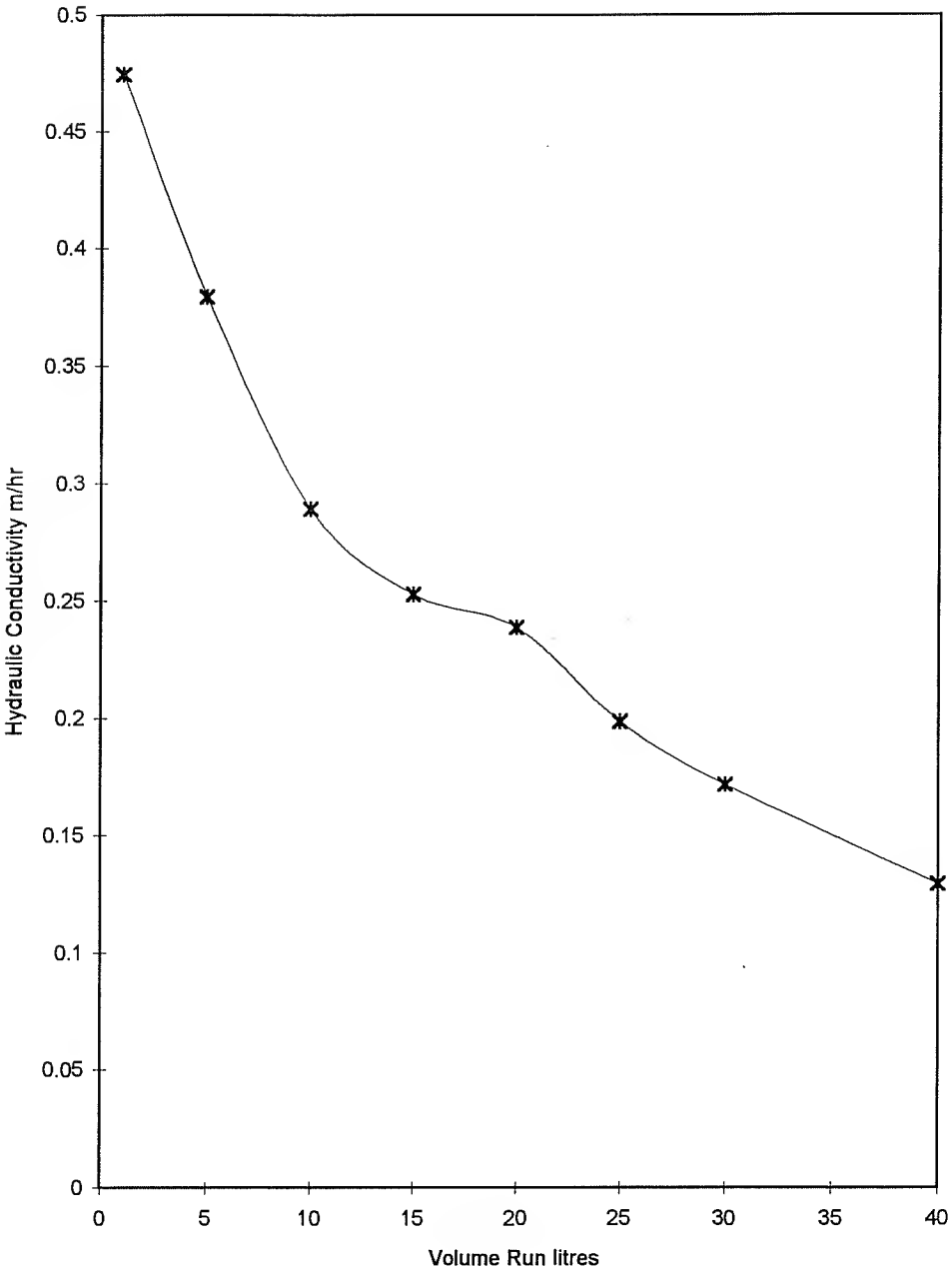

Figure 8.29 Change in Hydraulic Conductivity during Constant Head Test

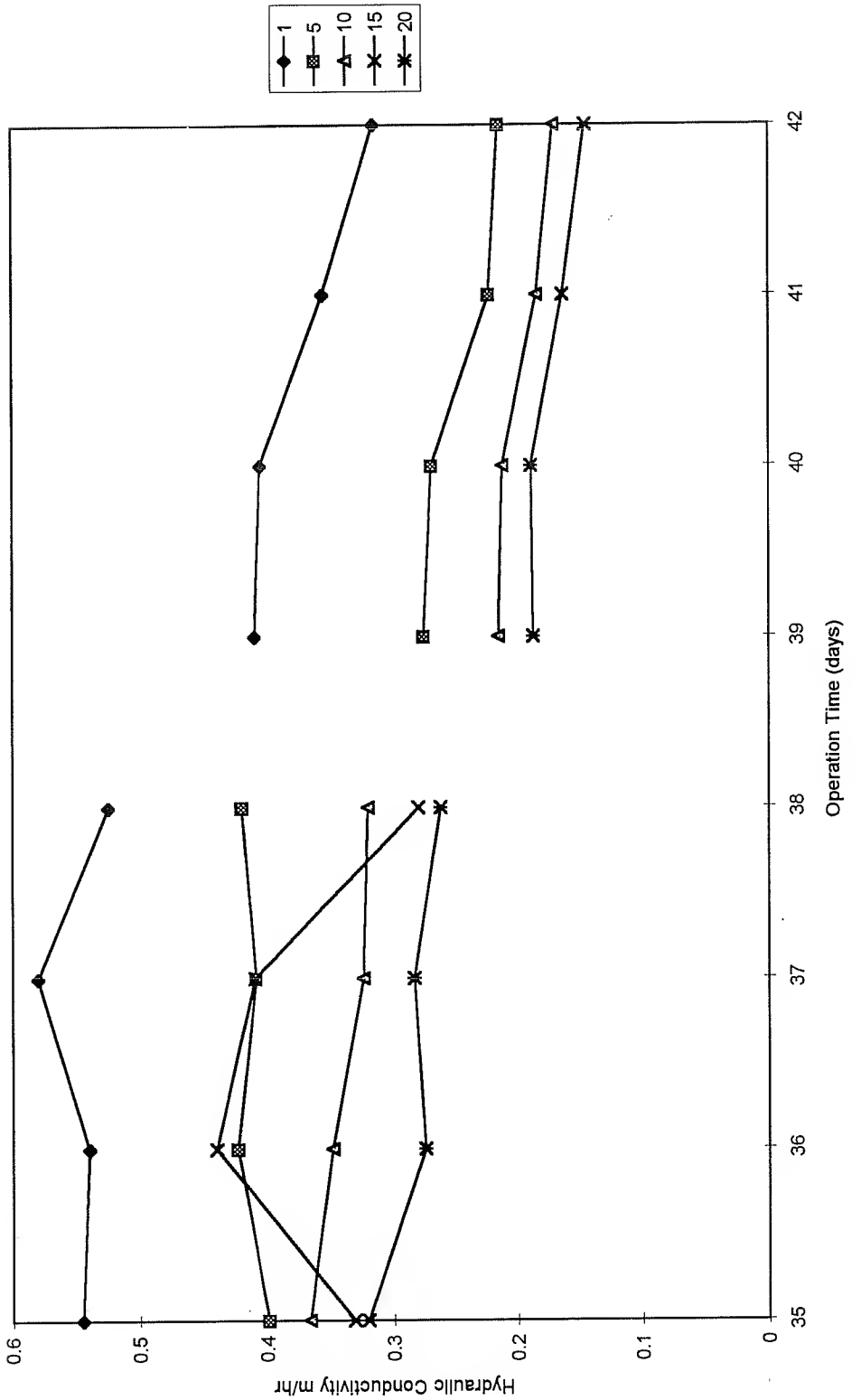

Figure 8.30 Reduction of Hydraulic Conductivity After Extended Run

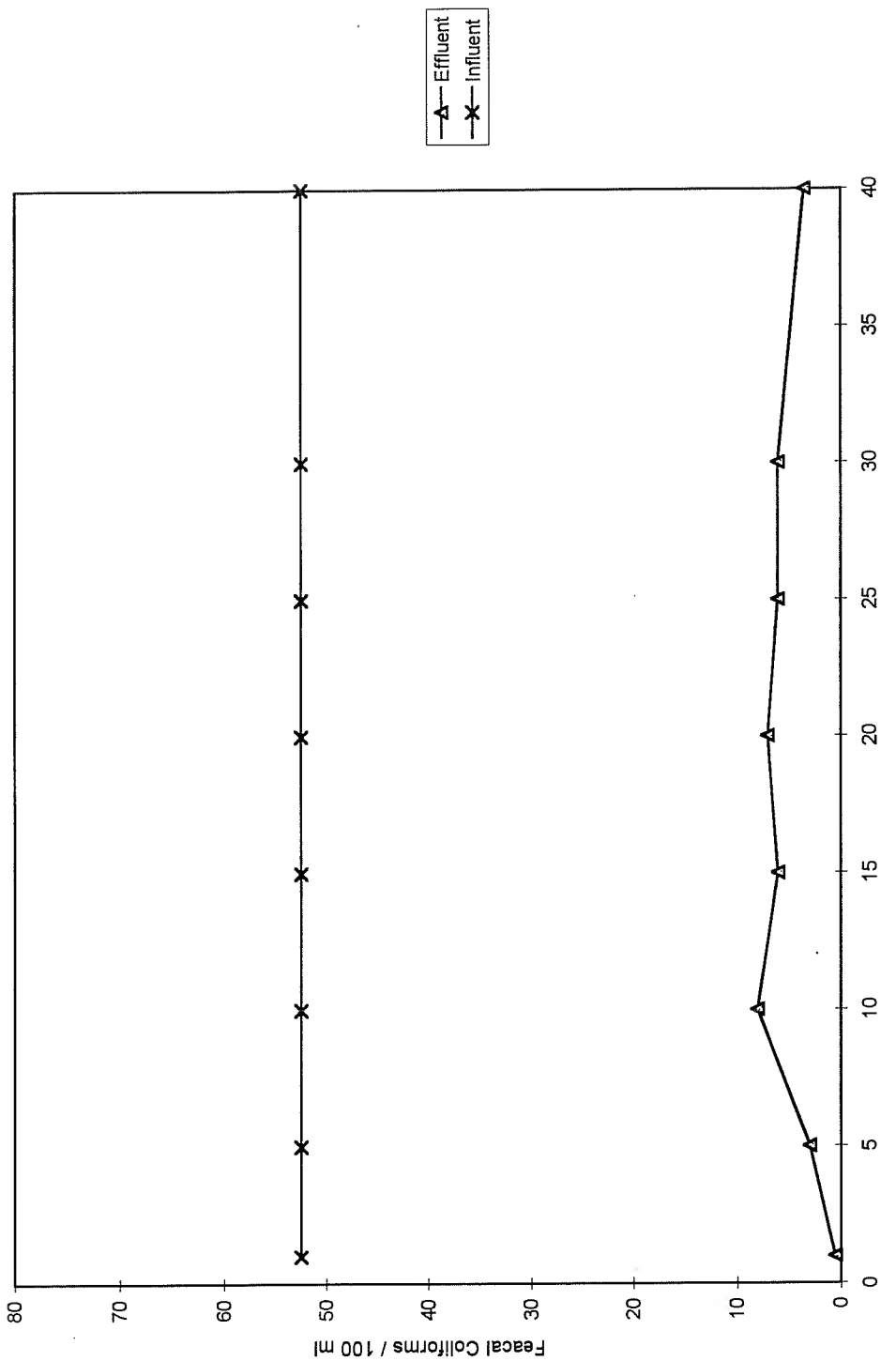

Figure 8.31 Faecal Coliform Counts During Constant Head Run

results were fairly sensitive to variations and the results are not as accurate as could have been expected if more highly contaminated water had been used. Figure 8.31 shows the faecal coliform counts over the constant head run. The figure shows the typical low values for the initial 10 litres increasing to a peak at 10 litres and then falling off as the flow rate declines. The values of measurements between 10 and 30 litres are virtually the same considering the 95% confidence intervals for values between 6 and 8 colonies/100mls.

From the above hydraulic conductivity data and faecal coliform data the flow rates of the different sampling points as they pass into the sand and the percentage faecal coliform removals were calculated and plotted against each other. This plot is shown in Figure 8.32. As with the plot for the normal 20 litre run the values for the 1 and 5 litre values were not expected to lie along the line because of there extended period in the filter. The figure confirms the relationship between flow rate and removal rate shown in Figure 8.25.

The plot of contact time vs. removal rate comparing this trend to oxygen use for different contact times, shown in Figure 8.33, show that the dissolved oxygen increases with volume towards the dissolved oxygen level of the influent mixed with supernatant. It is again apparent that the majority of biological oxidation of contaminants is accomplished over the pause time and that physical mechanisms in the schmutzedecke and filter skin are initially responsible for removing

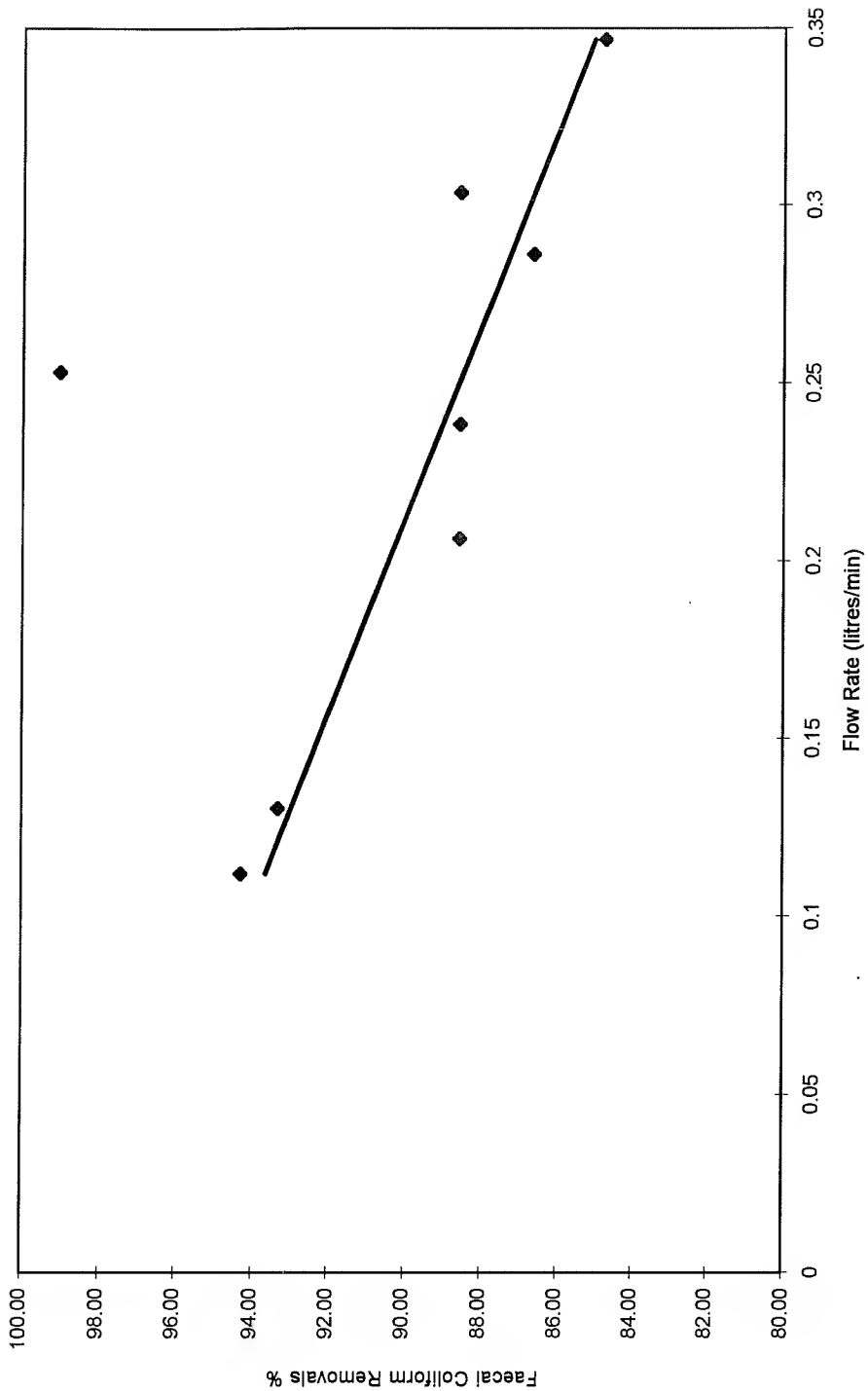

Figure 8.32 Flow Rate Through Filter Skin With Removal Rates during Constant Head Run

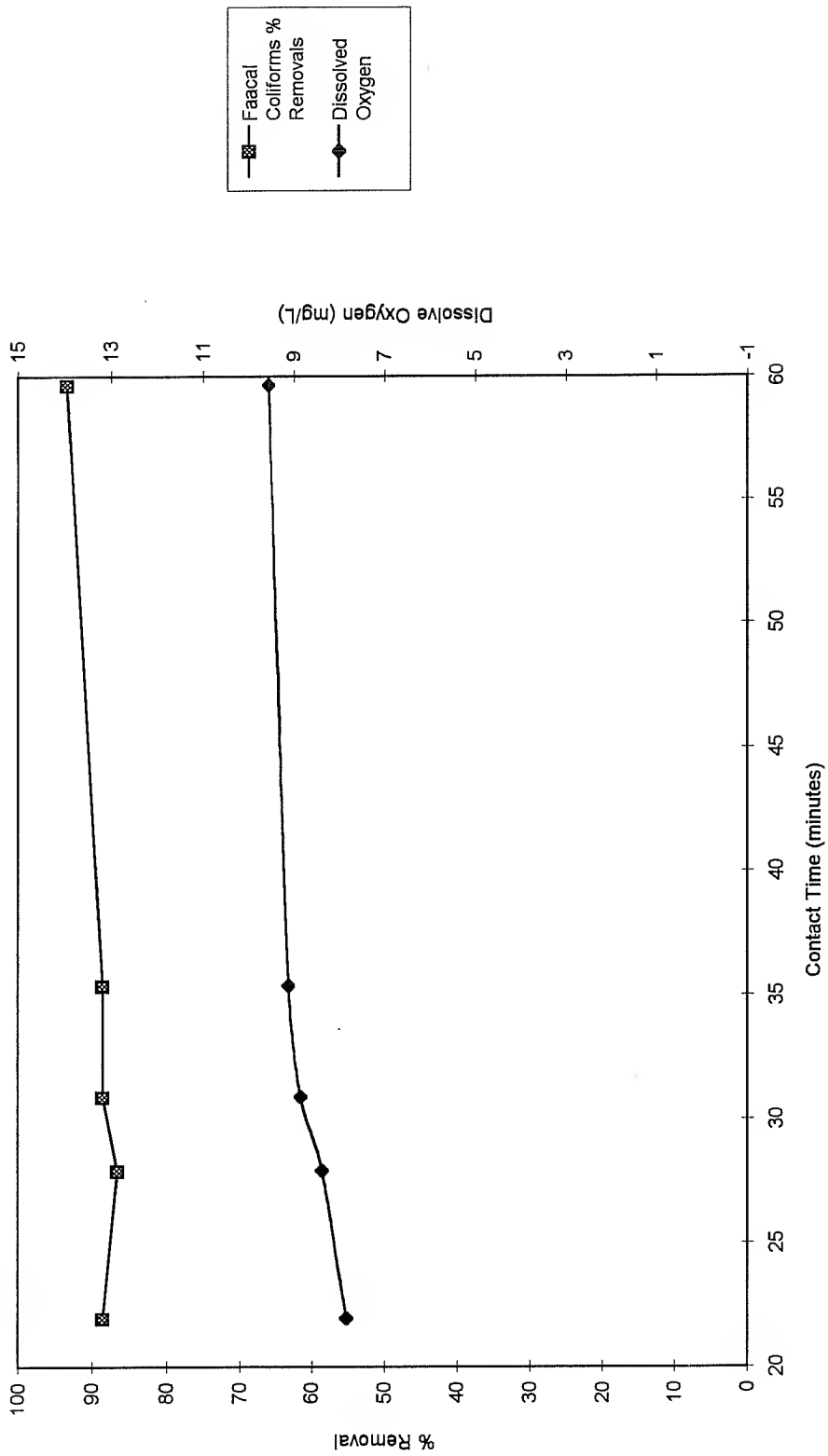

Figure 8.33 Dissolved Oxygen and Feacal Coliform Removal with Contact Time

contaminants. The data from the constant head run is in agreement with Figure 8.26 plotted for the typical values from a normal run.

8.10 Filter Commissioning

After the filter had been installed in the lab following the procedure described in the methods section, water was run through the filter until it became acceptably clear. In total approximately 40 litres of water was run until the turbidity of the effluent was less than 1 NTU. Figure 8.34 shows the decline in turbidity measurements as the volume run through the filter increased. The higher turbidities in the effluent initially were due to the washing from the filter of some clays, silts and fines that had not been completely removed from the sand by the initial washing process. After 40 litres had passed the effluent turbidity was 0.52 NTU. The water did clear relatively fast compared to filters installed in Nicaragua where people reported 60 to 100 litres being required before the effluent became acceptably clear.

Figure 8.35 shows the decline of faecal coliform counts as volume passing through the filter increased. The influent faecal coliform count is shown in the figure as well and was 10 faecal coliform colonies / 100 ml. The initial high faecal coliform counts in the effluent indicates that much of the faecal coliform contamination was ambient and then washed from the sand in the preliminary portions of the run.

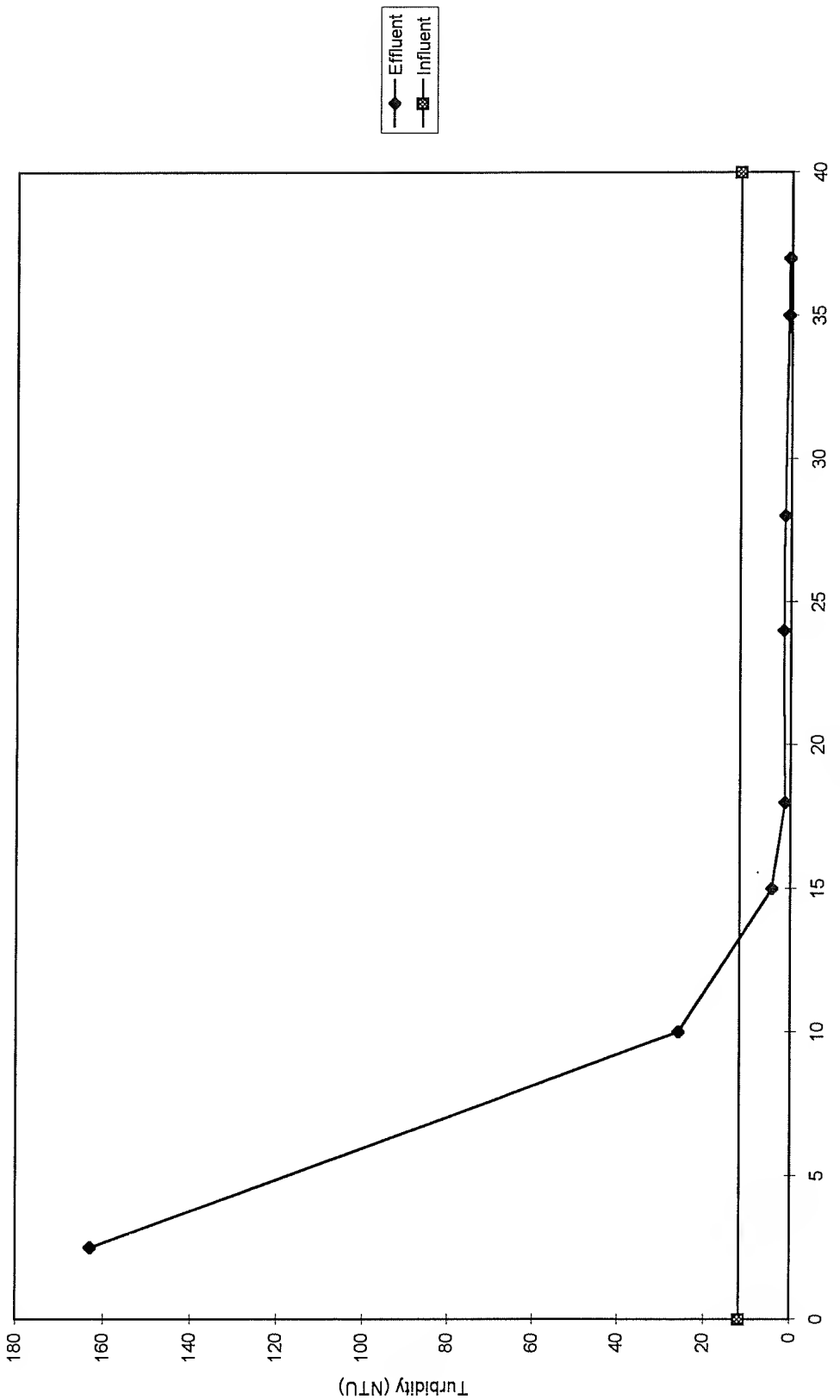

Figure 8.34 Turbidities Over Initial Run

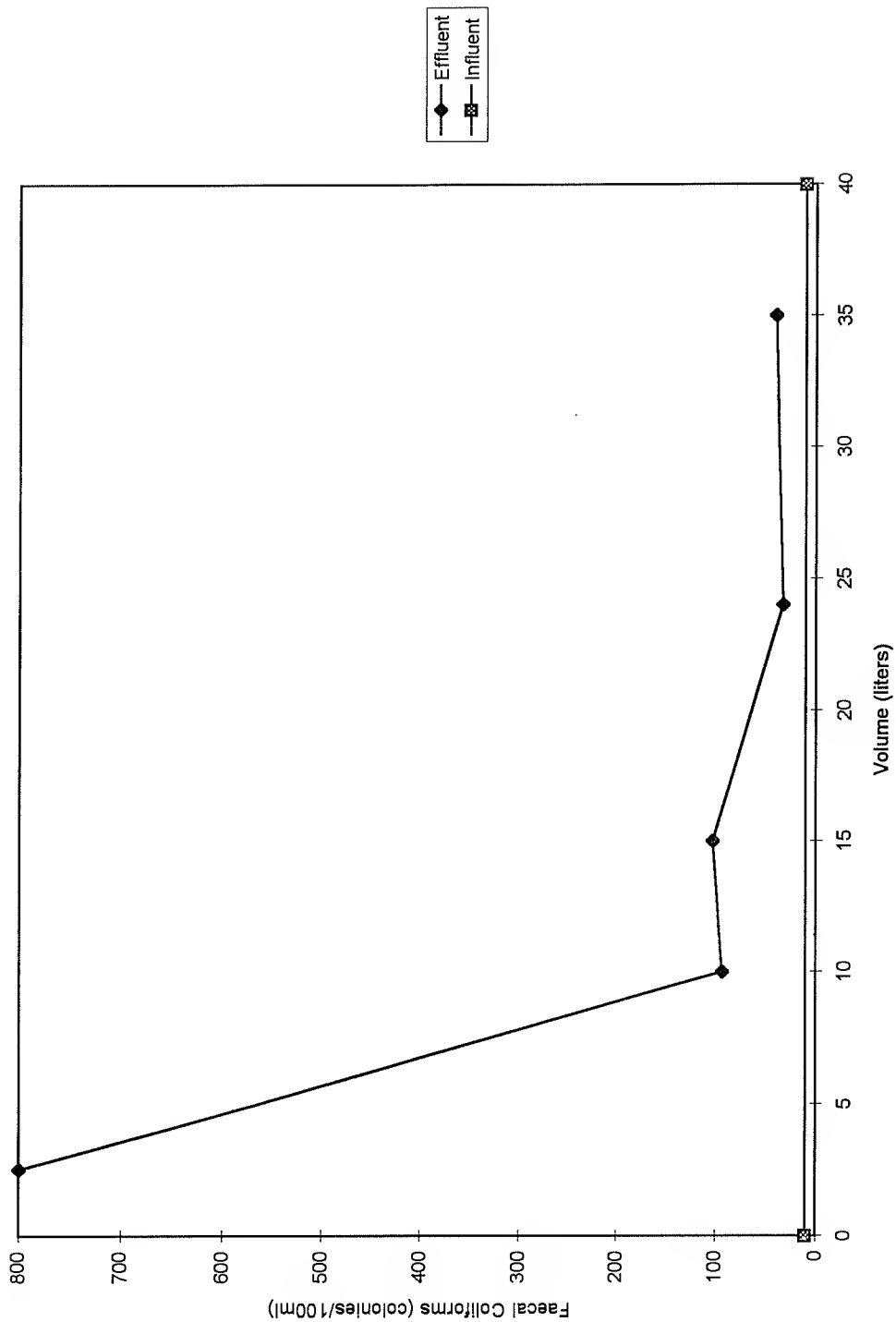

Figure 8.35 Faecal Coliform Counts During Initial Run

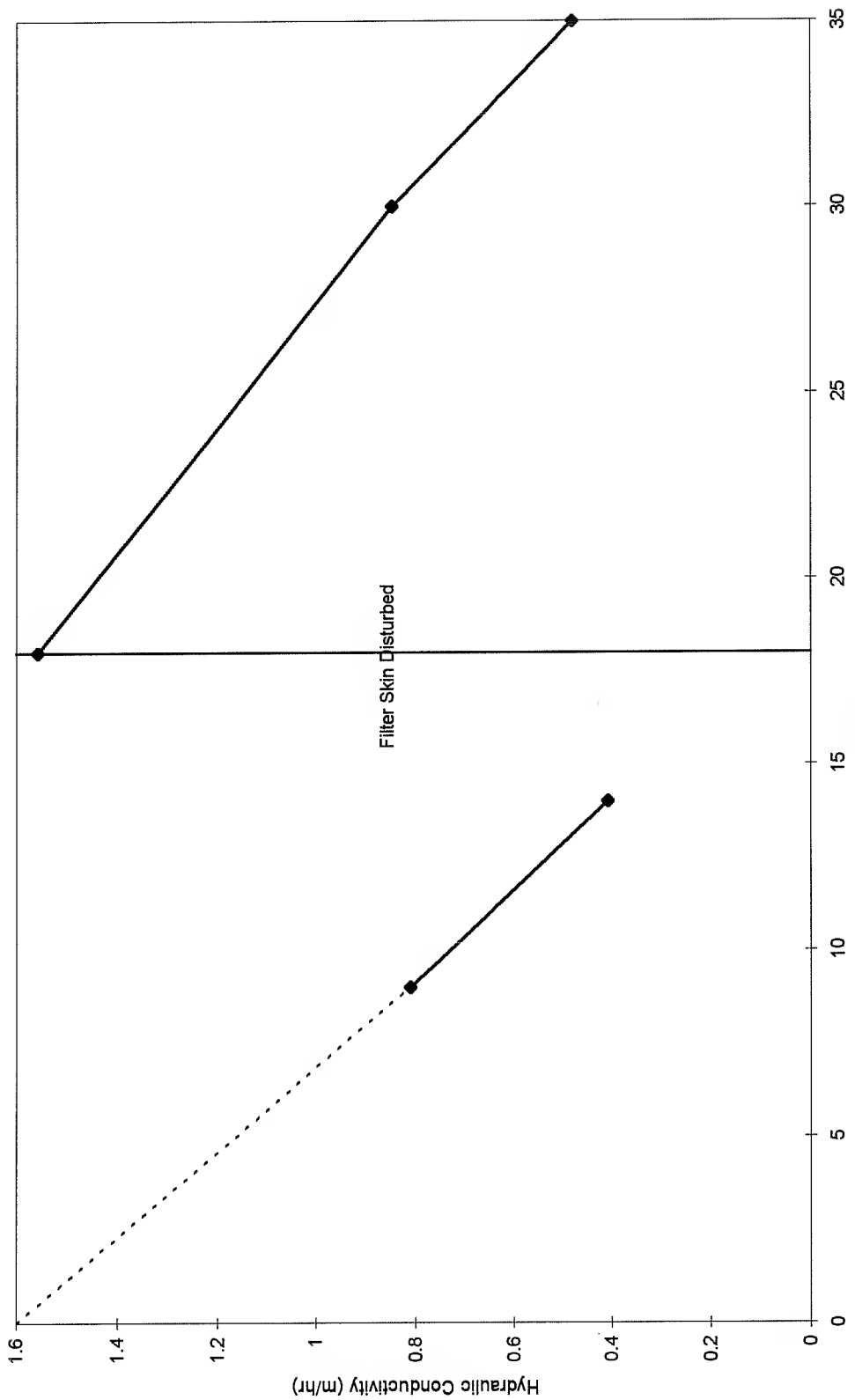

Figure 8.36 Variation of Hydraulic Conductivity during Comisioning

Hydraulic conductivities through the initial run varied dramatically as silt and clay settled out of the supernatant onto the sand surface. Part way through the run at 18 litres the surface of the sand was stirred up to remove the thin layer of mud that was apparently causing very significant head loss across the filter. Figure 8.36 shows the variation of hydraulic conductivity through the initial run, including the sharp recovery of conductivity at 18 litres.

8.11 pH and Electrical Conductivity Effects

Figure 8.37 shows the variation of pH over the entire experiment for the different samples. Initially pH values were very high and then declined approaching the influent values but did not reach them over the duration of the test. The effect seems to be linked to time in the sand bed since those samples spending the pause time in the sand and gravel had significantly higher pH, while the supernatant which remained relatively unchanged. The time effect theory is supported by the increases in pH of samples after both extended pause tests. The high pH is believed to be a contributing factor to the reported improvement in taste of the filtered water as the more basic pH gives the water a sweet taste. Figure 8.38 is a plot of the pH values determined by regressing lines onto the cumulative plots of pH. This was done in a similar way as the typical turbidity and faecal coliform counts were determined. The highest pH was associated with the 1 litre sample which spent the pause time in the gravel under drain. Initially, it was believed that

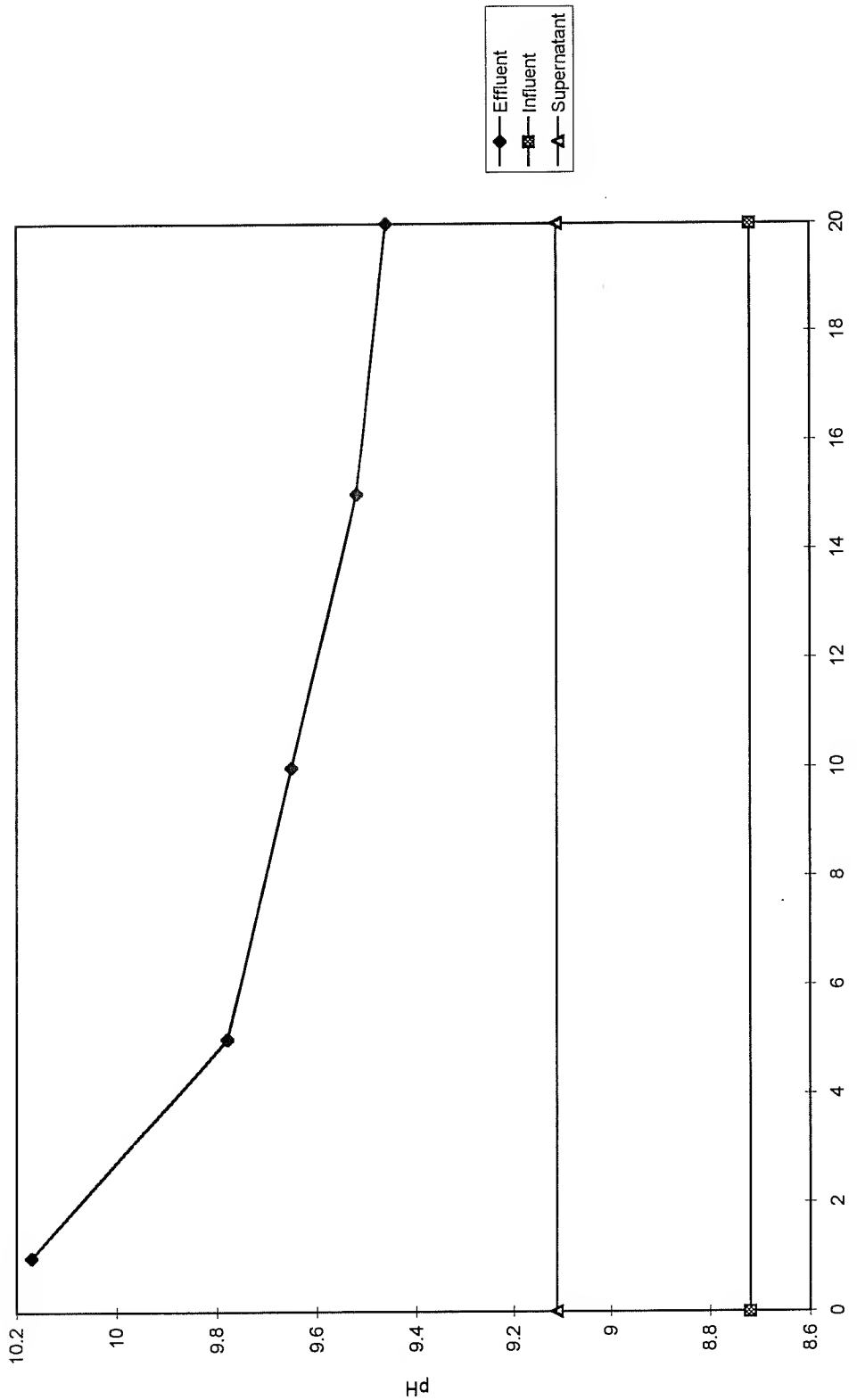

Figure 8.38 pH Variation Over A Typical Run

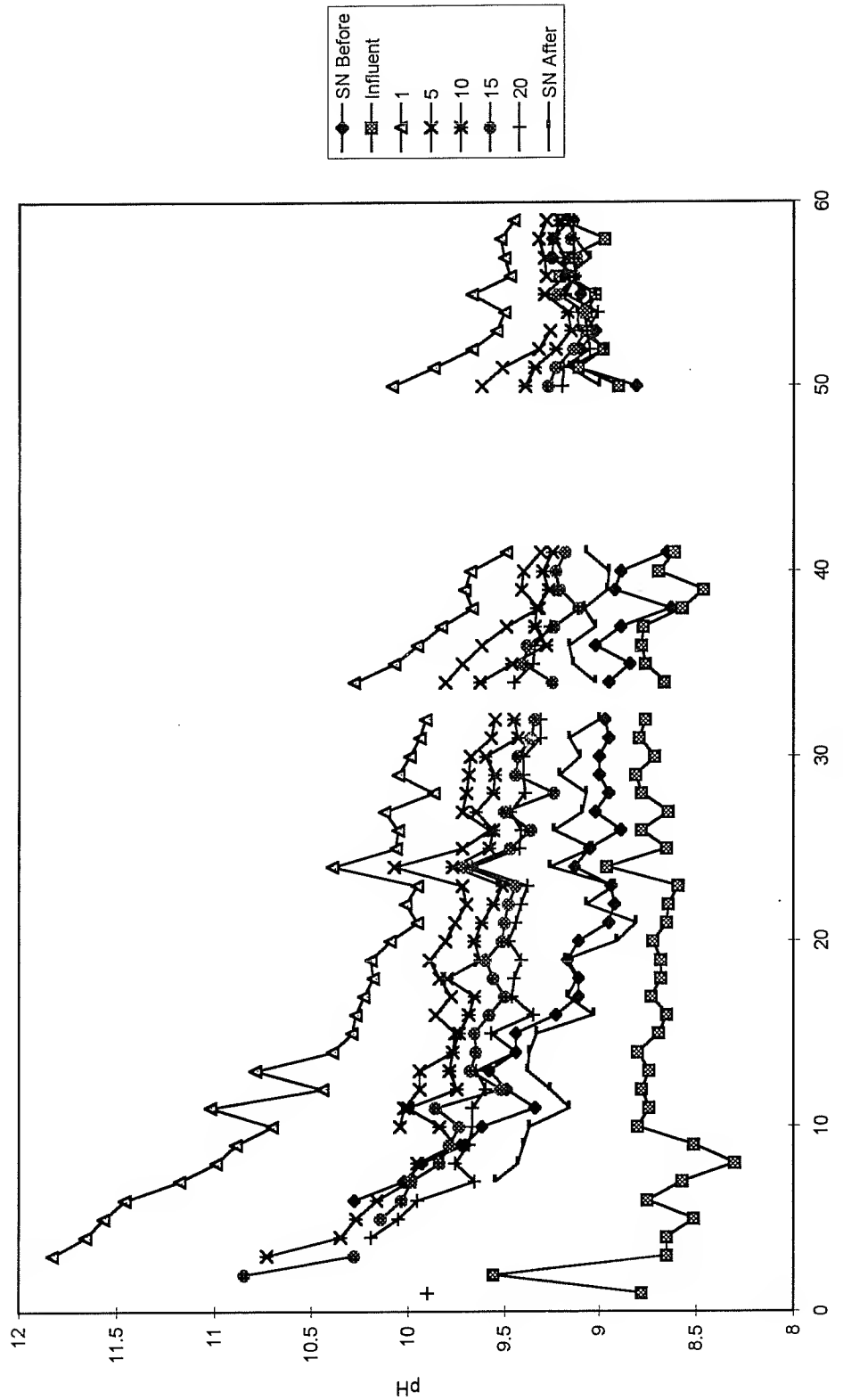

Figure 8.37 Variation of pH with Time

this pH increase was the result of the dolomite based gravel used for the under drain. This however does not explain results from the supernatant from filters operated in Nicaragua where basaltic stone was used. It was also suggested that the pH changes resulted from leaching of the concrete in the filter. This is unlikely since the water entering the concrete travels to the lower head outer surface of the filter where it is evaporated. In addition, tests of PVC filters showed similar drops in pH. To suggest that this is a result of some sort of biological process would lead one to believe that the biological layer is found mainly in the gravel layer and this is known to be untrue. It may be however an effect resulting from the chemical oxidation of bio-degradable organics which is offset by the metabolism of the microbes in the biolayer. In the lower portion of the sand bed where very little biological life is present the pH increasing effects of the chemical oxidation are not being offset by the biological production of pH reducing chemicals which is acting to bring the pH down in the 5 and 10 litre samples.

Figure 8.39 is a plot of the changing electrical conductivities of the different sample over the entire experiment. Some recorded values between 14 and 20 days were removed because the conductivity meter had low batteries and was providing inaccurate readings. As with the other data the cumulative plots were regressed to give typical values over a run. These are shown in Figure 8.40. As with the pH results the reason for the significant variation in the 1 litre sample is not clear at this time, however the two phenomenon appear to be linked in some way.

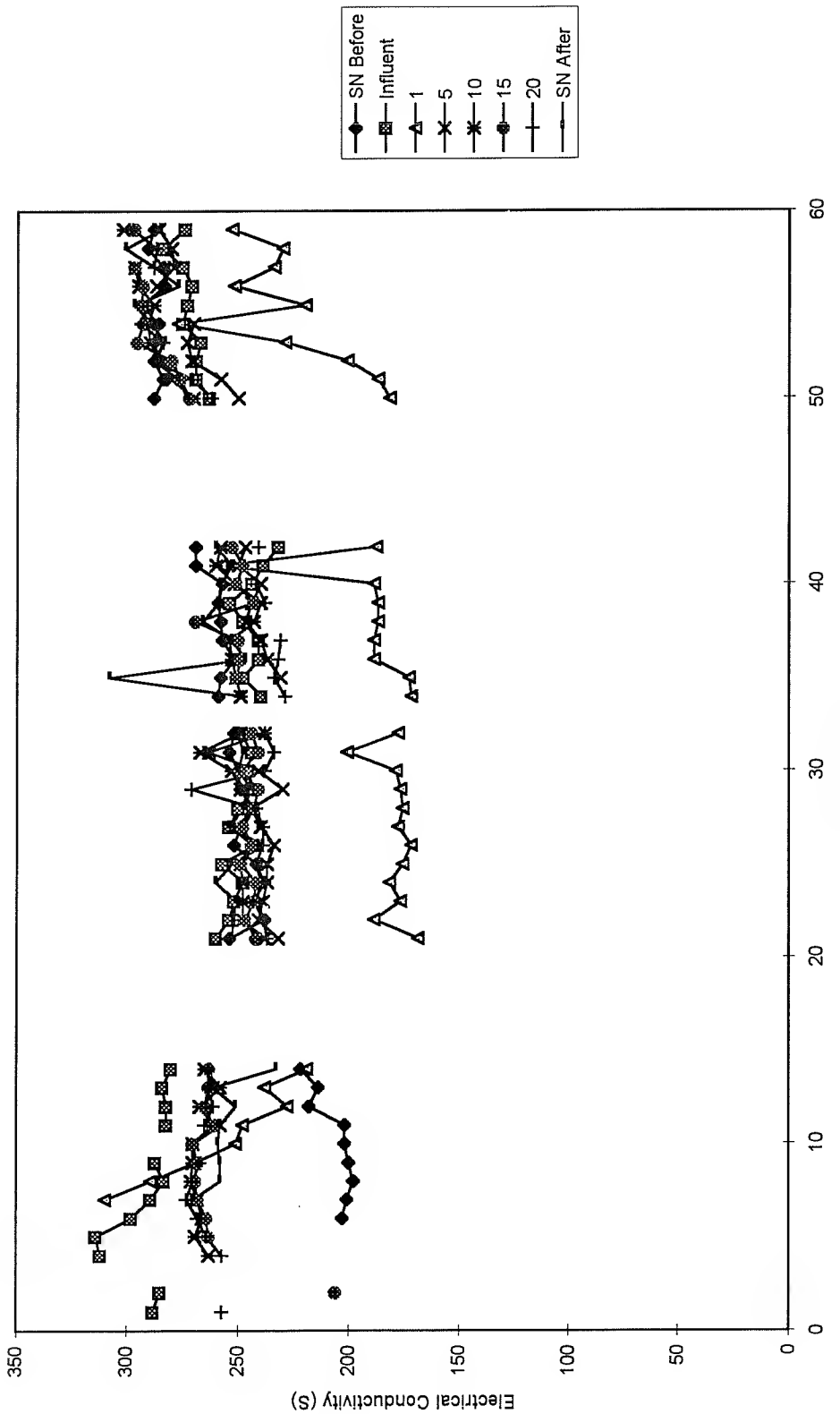

Figure 8.39 Variation of Electrical Conductivity with Time

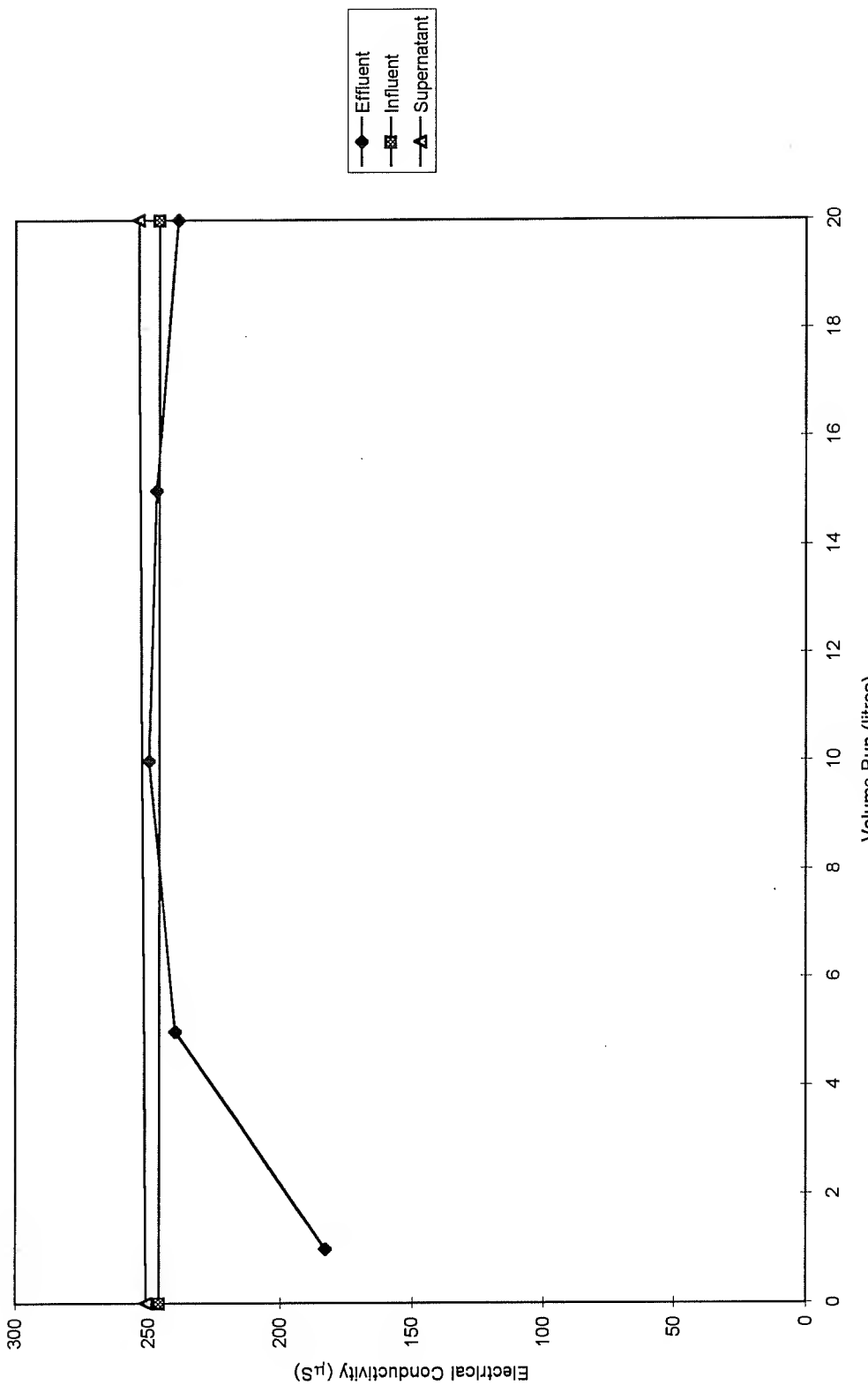

Figure 8.40 Typical Electrical Conductivities Over A Run

9.0 CONCLUSIONS

Un Gran Cosa!

- Francisco Vanega Gutierrez

The experimental results from the study show the effectiveness of the IOSS process and provide some insight for improving the removal efficiency of future designs. Several filter studies show that removals in excess of 96% can easily be obtained while filters operated with a consistent water source can expect even higher removals. The previous studies point out that a more shallow water depth is preferred since the two prototype studies having water depths 2.5 cm and 5 cm and filters installed with a 5 cm or smaller standing water depth in Nicaragua appeared to result in higher average removal rates than the 12.5 cm intensely studied filter (Manz and Buzunis 1995).

While no data was collected on actual pathogen removals, the anecdotal evidence shows the filter effectiveness in the general improvement in health and lack of cholera in the community using the filters. The reported aesthetic improvements and acceptance of the filters by the community citizens point out the effectiveness of the filter as judged by it's users. (Manz and Buzunis 1995)

The theory and dissolved oxygen model proposed for this process seems to be correct. The predicted shallow biologically active zone is supported by the dissolved oxygen data. The depth of the sand layer seems inconsequential except for the increased headloss and reduction of flow provided by a deeper sand bed. The depth of the biological layer is mainly a function of the depth of water over the sand bed since this controls the rate at which oxygen can be drawn down to the biologically active zone and the depth into the sand oxygen can be supplied. While the intensely tested filter had a biologically active zone less than 10 cm in depth, in filters with a more shallow standing water depth the biologically active layer is expected to be deeper. This would result in a longer contact time with the filter biology and improved filter efficiency.

Removal in the filter consists mainly of two phases. First the capture or the interception phase and second, the metabolism or consumption phase. The capture phase catches the contaminants in the sandbed and the metabolism phase consumes the contaminants, destroying pathogens and converting biodegradable substances to soluble biproducts. The combination of these two phases results in the decline of hydraulic conductivity over the run as the small pores in the filter skin are clogged and its recovery over the pause times when the filter skin pores are opened due to biological degradation of contaminants. This also causes a relationship between removal rate and flow rate which can be noted in the removal

efficiency dip associated with water occupying the biological layer during the pause times.

Oxygen is used in the metabolism of biodegradable components and the inactivation and consumption of pathogens. While the dissolved oxygen dip coincided with the drop in removal efficiency in the effluent, the decline in dissolved oxygen did not cause the removal efficiency dip. The decline in removal rate resulted from the incomplete metabolism of contaminants trapped in the upper sand layers. These were swept through the filter because of the high flow rate resulting from increased hydraulic conductivity of the biologically active zone.

9.1 IOSS Filter Performance

Generally, intermittently operated slow sand filtration can be expected to remove more than 96% of faecal coliform indicators and reduce turbidity to less than 1 NTU. It is expected that this process behaves in a similar way to COSS filtration and will remove very high proportions of pathogens, including parasites, cysts, viruses, bacteria and cerarcaie.

9.2 Design Recommendations

The design of the filter for effective removal of faecal coliform indicators requires a minimum water layer be maintained over the sand bed at all times. During the pause time the water layer should be as shallow as possible without allowing the sand to dry out. However the water layer should be deep enough to prevent scouring or disturbance of the filter skin when water is added to the filter.

The diffuser plate should be located as near to the water surface as possible to reduce the energy of water droplets as they fall into the standing water layer. Under no circumstances should the diffuser be at the standing water level or submerged during pause times as this will limit the effective area for oxygen transfer and limit the growth of the biological layer.

While it is known that the majority of biological activity occurs in the upper 10 cm of sand in the intensely tested filter. A more shallow standing water layer will increase the depth of the biological layer. Although evidence suggests that a sand bed depth between 20 and 30 cm should be sufficient to obtain high removals of faecal coliform bacteria, differences in the removal characteristics of other pathogens, such as viruses, support the use of sand bed depths as deep as reasonably possible.

9.3 Operating Recommendations

Flow rates through the filter should be kept as low as reasonably possible to improve removal rates. This can be controlled by deeper sand bed depths or lower available heads during operation.

Recovery of hydraulic conductivity can be accomplished by an extended pause, rather than filter scraping.

Hydraulic conductivity of the filters can be maintained by shortening operating periods and increasing pause times.

9.4 Further Studies

Priorities for further study include a more detailed look at the effect of flow rate, a study of sand bed depth as it afects removal rates, an investigation into the removal rate of the different classes of pathogens and a more detailed investigation of biolayer depth as related to standing water depth. These are just four investigations which are considered priorities since they will aid in defining the range of the various critical design parameters. Also, any investigation conducted for COSS filters can be done on the IOSS filter since the processes treat water in similar ways although nothing is directly transferable. In addition, modification of the process to treat other

waters such as waste water and larger scale applications were intermittent operation would be an advantage such as small community scale treatment facilities, should be considered.

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Appendix A

SUMMARY OF RESULTS FROM DEVELOPMENT OF A PROTOTYPE INDIVIDUAL SLOW SAND FILTER FOR INTERMITTENT USE IN THE PHILLIPINES

(Extracted from Lee 1991)

Daily Log from Lee 1991						
Date	Flow	Hydraulic	%		Comments	
	Time (s)	Loading	Coliform			
		(m/h)	Reduciton			
OCT. 22	738.74	0.79		clear, ordourless, some sand		
23	857.48	0.68			"	
24	766.49	0.76	undef.		"	
25	799.29	0.73			"	
28	788.88	0.74			"	
29	782.89	0.75			"	
30	819.10	0.71			"	
31	779.98	0.73	88.9		"	
NOV. 1	780.80	0.75		clear, ordourless, little sand		
4	800.69	0.73			"	
5	811.02	0.72			"	
6	803.78	0.73			"	
7	784.72	0.75	99.0		"	
8	810.95	0.72			"	
12	813.22	0.72		clear, odourless, no sand visible		
13	814.60	0.72			"	
14	825.41	0.71	98.5		"	
15	823.71	0.71			"	
18	827.06	0.71			"	
20	805.87	0.73			"	
21	815.50	0.72	99.7		"	
22	803.27	0.73			"	
25	800.52	0.73		clear, odourless, no sand visible		
26	847.15	0.69			"	
27	814.21	0.72			"	
28	800.75	0.73	91.7		"	

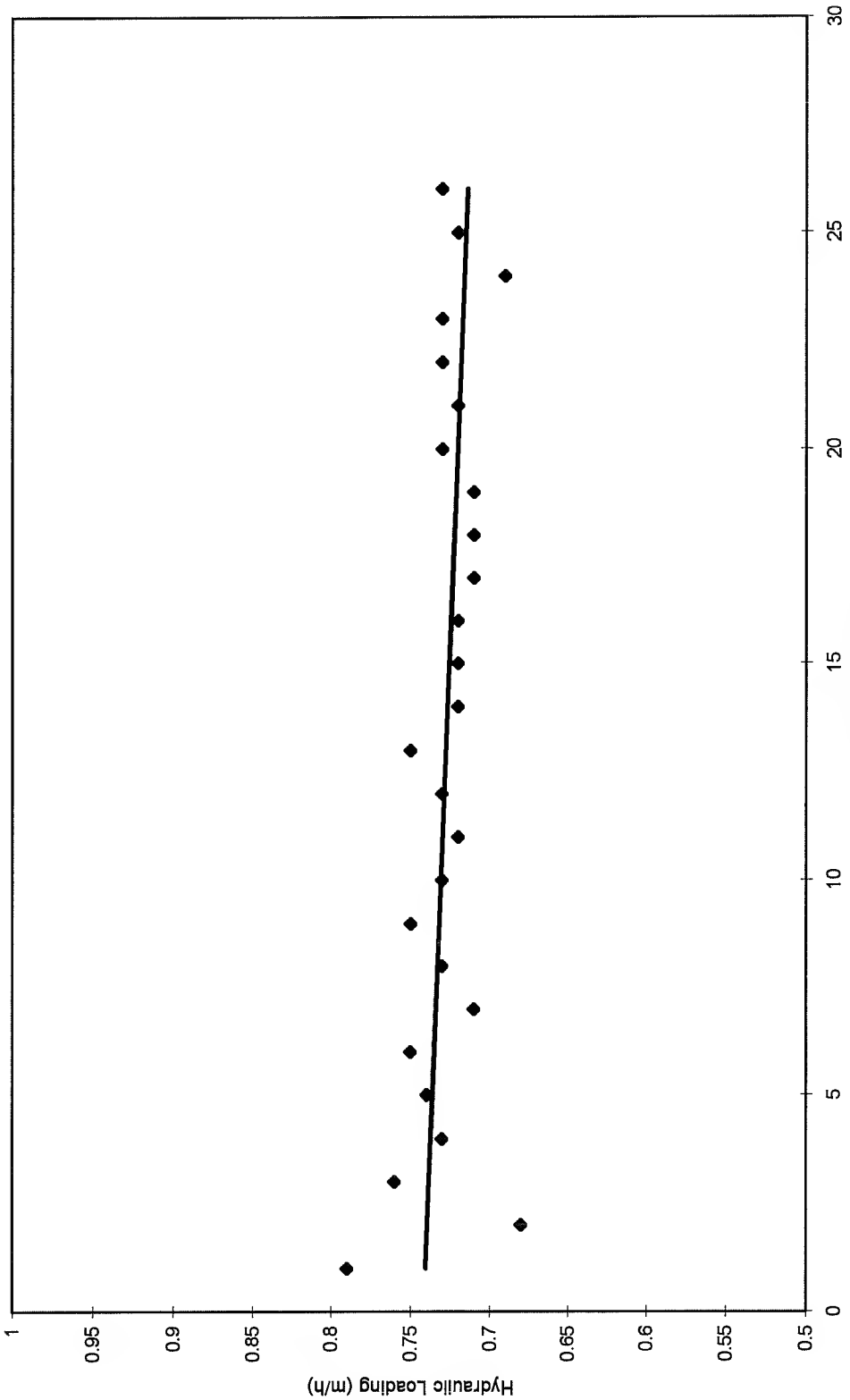

Figure A.1 Variation of Hydraulic Loading Rate

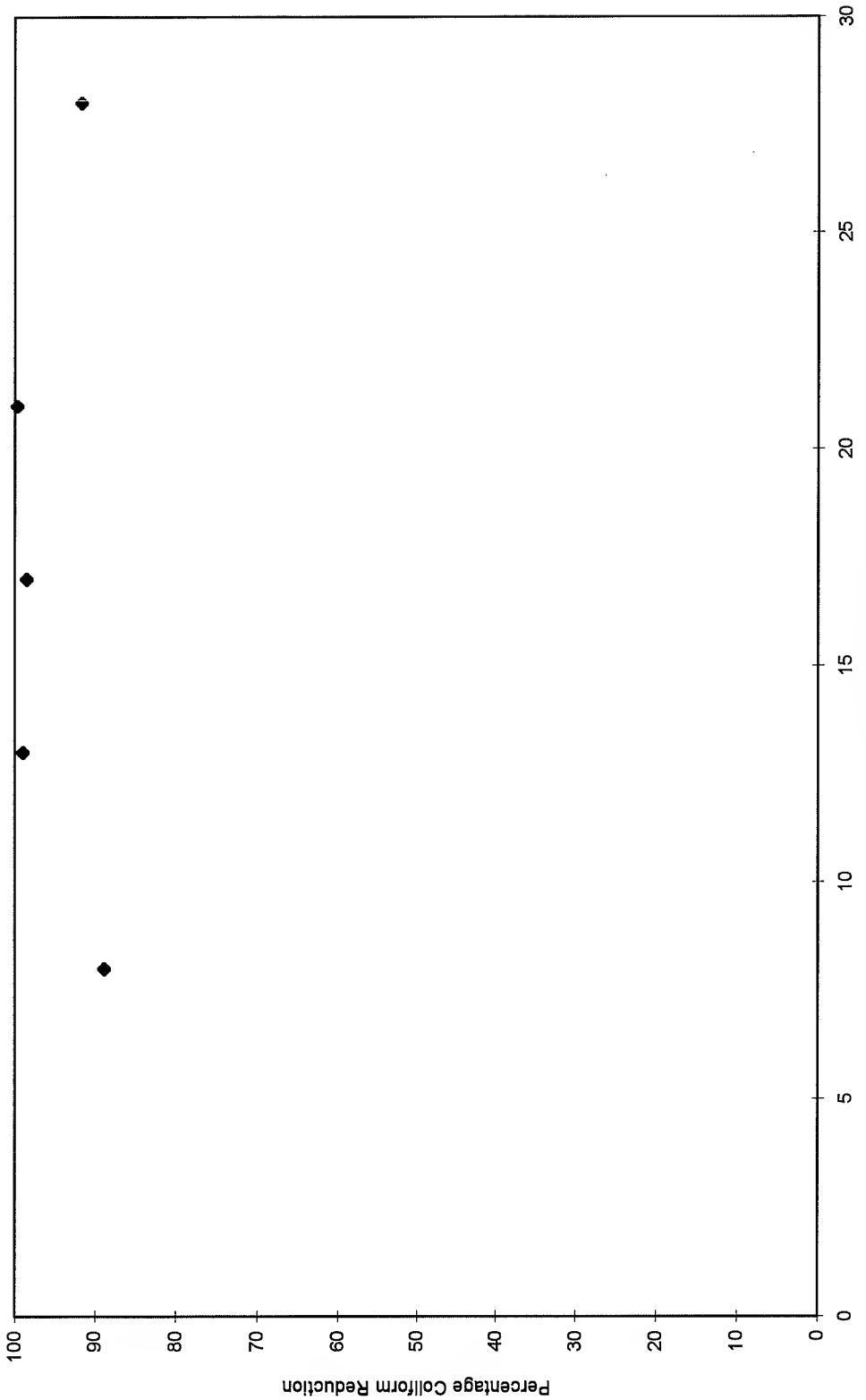

Figure A.2 Reduction in Total Coliforms

Appendix B

LABORATORY REPORT: CONFIRMATIONAL TESTING OF AN INTERMITTENTLY OPERATED SLOW SAND FILTER

By: Byron J. Buzunis

December 1993

B1.0 Introduction

A world-wide problem is providing dispersed rural communities with potable water. While adequate quantities of water maybe available many water sources are contaminated. This is a significant expense both in terms of lives and productivity as well as in terms of obtaining new water sources or treating water. The problem is compounded in developing countries where conventional solutions are expensive and inappropriate and traditional solutions are not effective. The development of IOSSF resulted from the need of dispersed rural communities for potable water. The IOSSF has been designed to ensure simple operation and maintenance, low cost and effective removal of diseases.

In September 1991 testing of the original prototype was began as the topic of an undergraduate thesis. This research showed removal rates for the IOSSF of more than 99.8% after the development of the biological layer (Lee 1991). Based on these results and on interest from the DESAPER project through DID and other development organisations. This study was commenced in order to confirm the initial results.

B1.1 Objectives

The objective of this study was to confirm the results of David Lee's undergraduate thesis project. This experiment attempted to eliminate some variables to determine the variables important to the process. In addition the research was undertaken to evaluate the laboratory established as part of another undergraduate thesis. This was accomplished through comparison testing by the provincial laboratory of public health.

B2.0 Apparatus

The experimental apparatus is shown in Figures B.1 and B.2. Figure B.1 shows the influent producing and handling equipment which consisted of a 45 gallon drum used to dechlorinate city tap water and a 30 gallon garbage pail used as a tank into which dechlorinated water and small amounts of dog faeces were added to produce contaminated water. Both of these tanks were aerated.

Figure B.2 shows the IOSSF used in this study. The filter consisted of a length of 25 cm diameter PVC pipe 100 cm tall. The bottom was closed and sealed to be water tight with a plastic plate and silicon sealant. An underdrain was constructed from 3/4 inch PVC pipe and located 5 cm above the filter bottom.

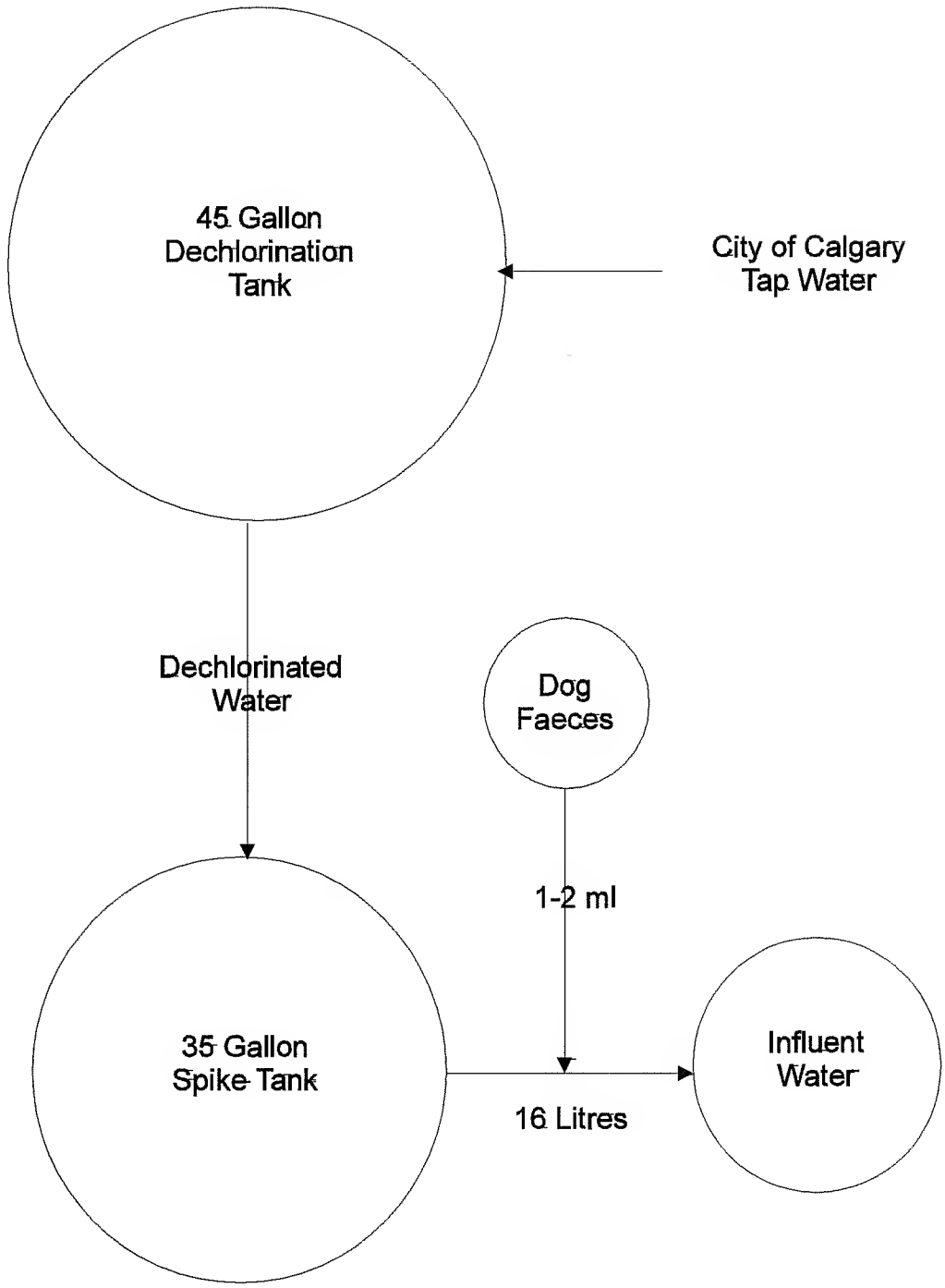

Figure B.1 Influent Handling Equipment

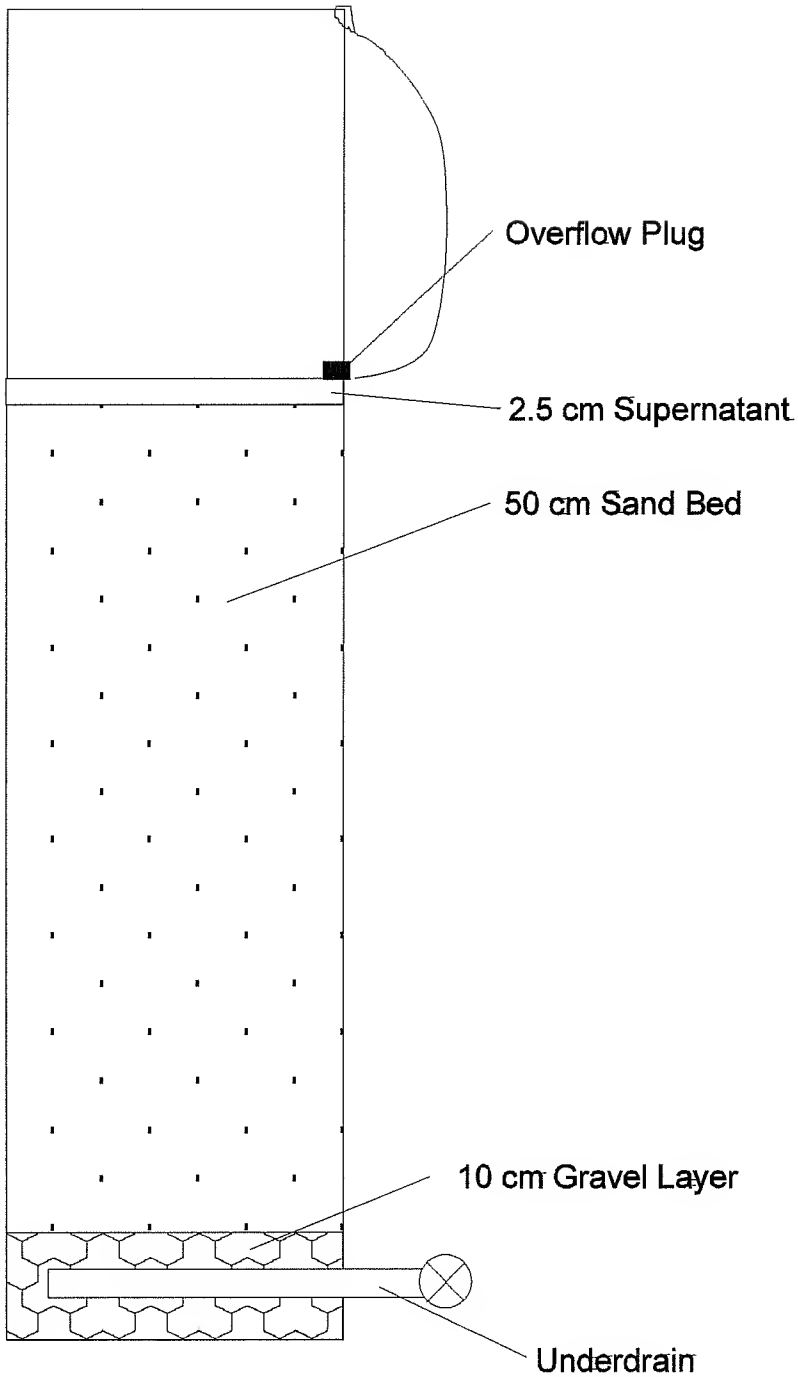

Figure B.2 Sketch of PVC pipe IOSS Filter

The underdrain had 1/4 inch holes drilled in a line along the bottom at intervals of 1 inch. The flow of water from the filter was controlled by a valve on the underdrain outlet.

The media for the filter consisted of construction gravel and sand. The 14 mm gravel was rinsed to remove clay silt and rock flour and placed around the underdrain forming a 10 cm deep layer. Above the gravel a 50 cm layer of sand was placed. The sand had a U. C. of 5.5 and a d_{10} of 0.20 mm. Prior to being placed in the filter the sand was rinsed to remove some silts and clays. This will have increased the d_{10} and lowered the U.C. slightly since some of the fines have been removed.

A supernatant drain hole was drilled 2.5 cm above the sand surface to allow for the control of supernatant water depth during pause times. A special funnel was constructed to facilitate adding water to the filter without disturbing the sand bed. This consisted of a funnel to which was connected a container filled with coarse gravel. In the bottom 1 cm of the containers sides many 2.5 mm holes were drilled to direct the velocity head of the water horizontally and protect the sand bed.

B3.0 Methods and Procedures

After constructing the filter and placing the sand and gravel, water was run through the filter until the effluent became clear. Daily 16 l of water was run through the filter. This water was prepared by adding 2 ml of dog faeces to 16 l of water from the spike tank. After removing the 16 l of water from the spike tank it was replenished with water from the dechlorination tank. The dechlorination tank was then refilled with city tap water. To ensure a wide diversity of microbiology the original spike tank water was obtained from the effluent channel of Bonny brook water treatment plant.

Water samples were taken for faecal coliform tests of the Influent and of the effluent near the end of the run once total replacement of the water in the filter had taken place. Occasionally duplicate samples were taken for analysis by the Provincial Lab of Public Health. Flow rates were recorded three times through out each run when the water level in the filter reached a specified location.

B4.0 Results

Table B.1 summaries the results of the studies performed to verify filter effectiveness and aid in design development.

Table B.1 Summary of Prototype IOSS Filter Study

Prototype Filter II PVC pipe filter				
Date	Days After	Faecal Coliforms		
		Influent	Effluent	Removal
93/02/5	14	950	150	%84.21
93/03/10	27	12300	2	99.98
93/03/15	32	508000	185	99.96
93/03/16	33	6850	88	98.72
93/03/17	34	6000	51	99.15
93/03/23	40	5800	22	99.62
93/03/25	42	2000	2	99.90
93/04/05	53	1000	0	100.00
93/04/12	60	18350	203	98.89
93/04/19	67	>>200000	176	>>99.12
93/04/26	74	11000	44	99.60
93/05/03	81	34000	32	99.91

The table and the following graph Figure B.3 summarize the results obtained from the PVC pipe filter experiment.

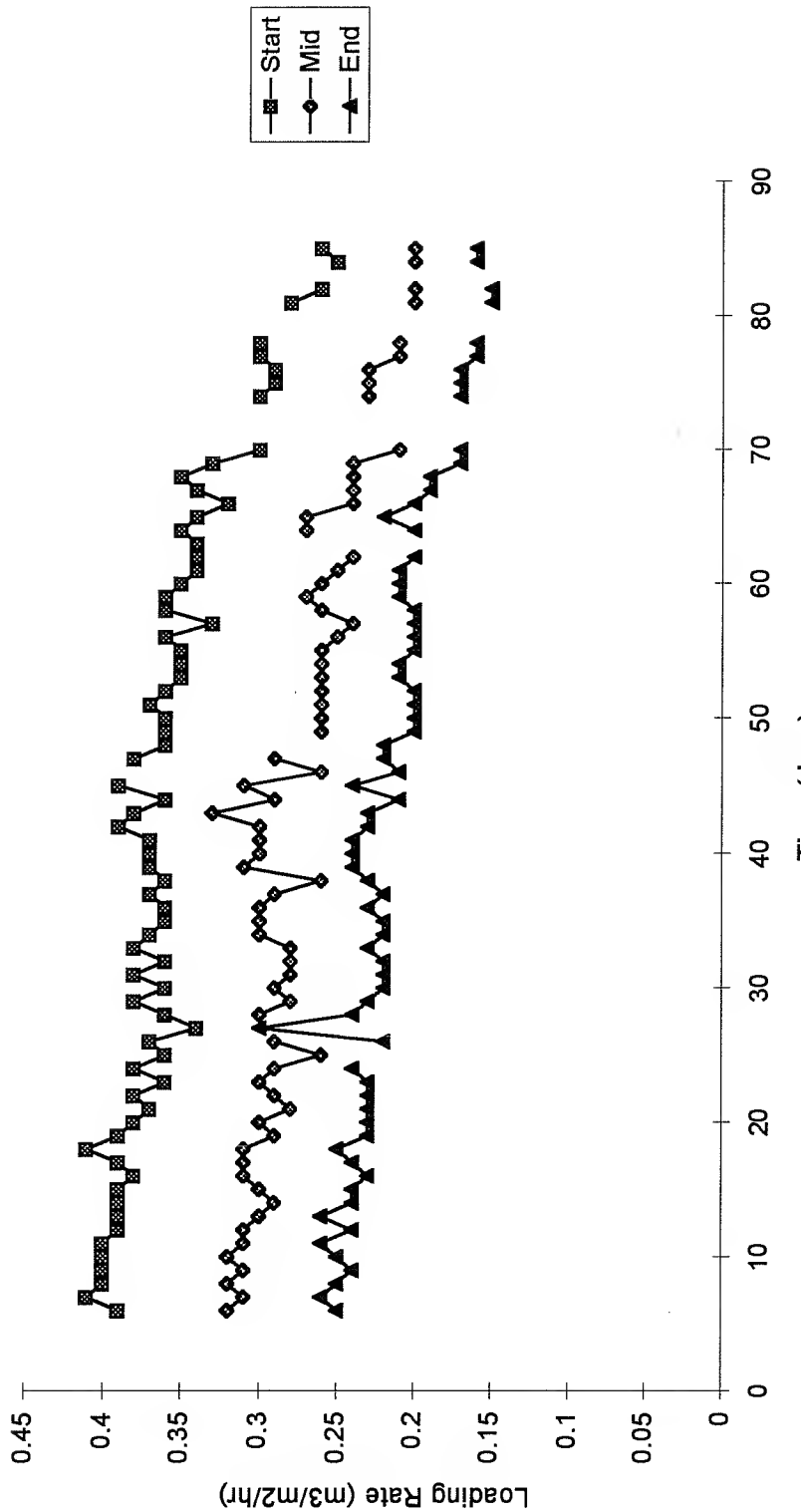

Figure B.3 Variation of Loading Rate with Time

B5.0 Conclusions

The results from this experiment confirm that effective operation of an intermittently operated slow sand filter is possible. The use of a more shallow controlled water depth and a slightly deeper sand bed and lower loading rate than used by Lee 1991 have, in general, increased the removal efficiency of the filter. Over the duration of the test the hydraulic conductivity decreased indicating that the flow rate would by halved after about 240 days.

B6.0 References

Lee, D. (1991) Development of an Individual Slow Sand Filter for Intermittent Use in the Philippines, Report completed for an undergraduate coures, Department of Civil Engineering , University of Calgary, Calgary, Canada

Appendix C

LABORATORY REPORT: SUMMARY OF CONCRETE PROTOTYPE STUDY

Byron J. Buzunis

December 1993

C1.0 Introduction

The need for clean water is apparent in the developing world. This water must be provided in a culturally acceptable and cost effective way. As a result of observations made by the author and David Manz on a preliminary reconnaissance trip to Nicaragua in February 1993 a concrete filter design was developed. Construction of wash basins, barbecues and toilets from concrete is a wide spread indigenous skill in Nicaragua.

C2.0 Description of Concrete Filter

This concrete filter was 1.066 m high and included a depth of 0.406 m below the diffuser plate for sand bed gravel layer and standing water depth. the underdrain was constructed from 5 cm diameter ABS pipe. This filter used a goose neck pipe to provide an overflow type control for the water depth in the filter and a concrete diffuser plate. The underdrain gravel was 14 mm gravel from the concrete laboratory and had a depth of 18 cm. The sand bed was 17 - 20 cm deep and a 1-2 cm water layer was provided during rest periods.

The water used for this experiment was drawn from the University of Calgary sprinkler system. This water is piped directly from the bow river so, the faecal coliform contamination in the influent was lower than hoped. All samples for this experiment were analysed by the Provincial Lab Of Public Health.

C3.0 Results

Table C.1 summarises the results of the prototype concrete filter experiment.

Table C.1 Summary of Concrete Filter Results

Prototype Filter III Concrete Filter				
Date	Days After	Faecal Coliforms		
		Influent	Effluent	Removal%
93/07/06	2	<10	1	<90.00
93/07/13	9	10	0	100.00
93/07/21	16	<10	0	100.00

Even with the very shallow sand bed high removal rates were obtained very quickly although this is likely due to the low concentration of indicators in the influent. Over the 32 day duration of the experiment the initial flow rate, right after influent was added, declined from about 0.70 m/hr to 0.48 m/hr.

C4.0 Conclusions

The concrete container does not adversely effect filter performance and so is a viable alternative for developing countries like Nicaragua which have concrete manufacturing skills. Even though a shallow sand bed, 20 cm, was used excellent removals of indicators were obtained though this could be partially due to low influent concentrations of indicator organisms.

Appendix D

THE THREE PVC PIPE IOSS FILTER EXPERIMENT

Byron J. Buzunis

September 1995

D.1 Apparatus

Each filter consisted of a 10 to 15 cm inside diameter PVC pipe about 2 m long. The filters were instrumented with piezometers and sampling ports at various levels for bacterial, DO, pH and turbidity sampling. Figure D.1 is a sketch of the apparatus used. An access door was provided for each filter. The access door facilitated placing the sand bed, required filter scrapings and allowed for observations. A riser pipe was used to control the water depth over the sand during pause times. An upper over flow was provided in each apparatus to ensure head at the start of each run is consistent for each filter. A diffuser plate in each filter was located at a height of 2 cm above the water level in the filter during pause times. The purpose of the plate is to dissipate the energy of the inflow water and prevent it from disturbing the sand bed and filter skin

The COSS filter used in these experiments had a similar design to the intermittently operated filters and used the same sand, and sand bed depth. This filter was run in conjunction with the others to allow a comparison of the two processes.

The sand used in these experiments has a d_{10} of 0.25 mm and a UC of 5. A sandbed depth of 50 cm was used in all filters. Relationships between removal rates and sand bed depth are established through the use of sampling ports

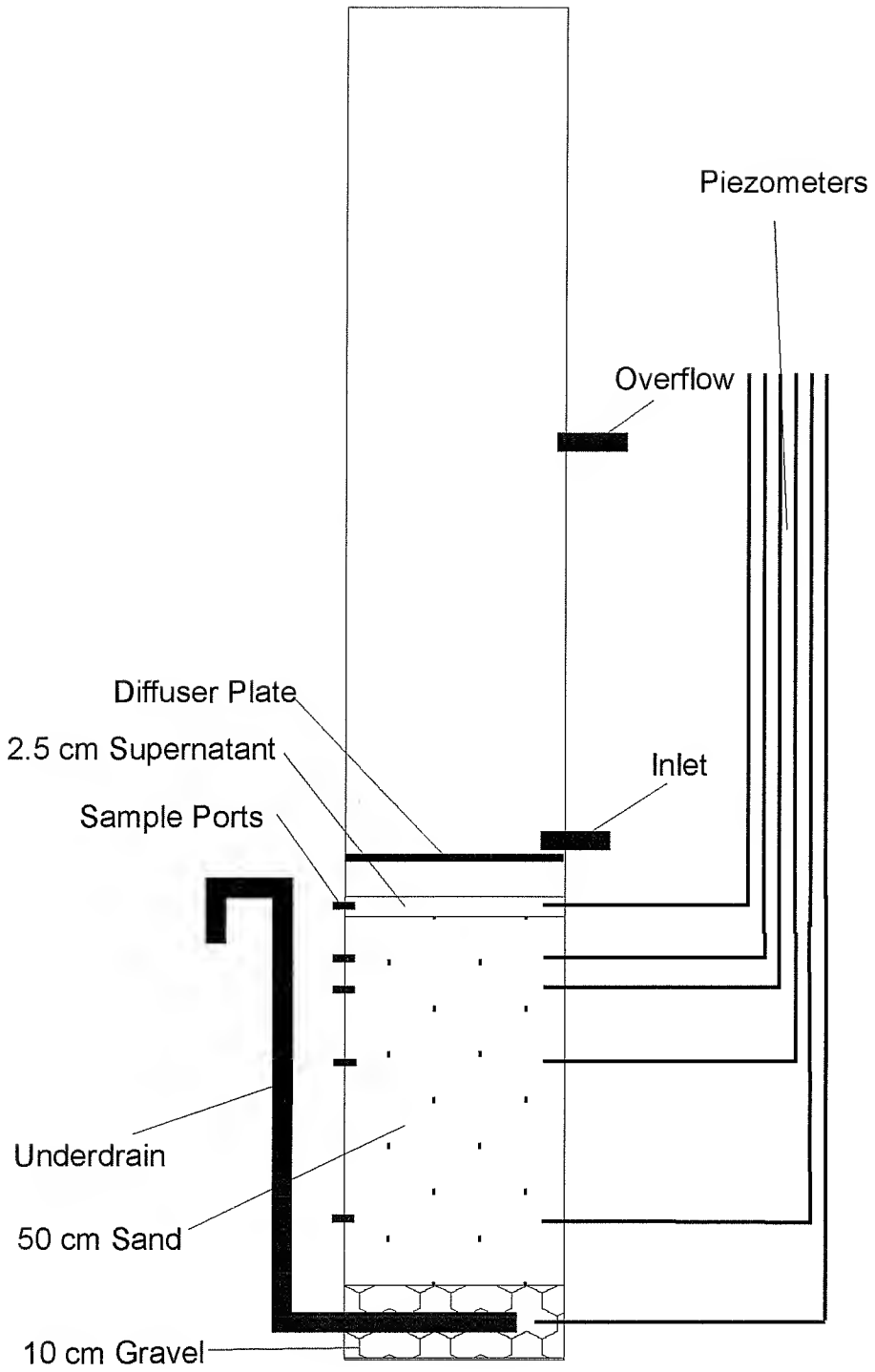

Figure D.1 PVC Pipe Filter I with 2.5 cm Standing Water Depth

located at 10, 20, 40 and 55 cm below the sand surface. Rather than using several layers of graded gravel the underdrain consisted of a 10 cm depth of washed 14 mm construction gravel. The lowest sampling port is also the normal underdrain pipe of the filter and consists of a 1/2 inch pipe with 1/4 holes drilled in the bottom.

To make the tests comparable ambient conditions of temperature and influent water quality will be consistent for the all filters. Up to this point it has been difficult to produce a consistent water for influent. However, a chemostat was built to batch a continuous highly concentrated solution of a diverse population of micro-organism and faecal coliform bacteria. The chemostat had a volume of about 20 litres and was kept at a temperature of about 35 °C and aerated. Media for bacterial growth included powdered sugar, common garden fertiliser and raw hamburger. Fresh media was prepared by dissolving high concentrations of the constituents in water. This sterile media was then added to the chemostat. The initial diversity of organisms was obtained by using secondary effluent from a nearby sewage treatment plant which contained about 200 000 faecal coliform per 100 ml as well as a high diversity of other organisms

Influent water for the filters was produced by dechlorinating city tap water in an 45 gallon drum. This water was then transferred to the influent tank from which

the filters were supplied. Frequently, a small amount of concentrated solution from the chemostat would be added to the supply tank to produce influent water with a concentration of about 5000 faecal coliform / 100 ml. This very high concentration was used to reduce the size of water samples taken for bacteriological analysis and thus allowed the use of smaller surface area filters and required the handling of less water.

The IOSS filters where operated by pumping water from the influent tank into the filter until the upper overflow was reached in all filters. After 30 minutes the pump was shut off and the water flowed out under declining head until the lower water level was reached. The lower water level was controlled by the positioning of the outlet of the filters. The volume of water filtered was enough that during a normal run the entire volume of water in the filter with the deepest standing water depth had been replaced. All IOSS filters were run once every 24 hr period. The COSS filter was operated continuously at a rate of 0.20 m/hr and the outlet control valve was adjusted as necessary to control the rate. The filtered water was return to the Influent tank after the filtered water tank had been filled. This occurred about half way through the run. When the influent water tank was again spiked it was also topped up from the dechlorination tank. Both tanks and the chemostat were monitored frequently so that indicator organism concentrations could be controlled.

D2.0 Experiments

The critical variable is water depth allowed over the sand bed during pause times. This is the single variable which makes intermittently operated slow sand filtration a unique process. The relations ship of water depth over the sand to the bacteriological removal efficiency of the filters was examined by constructing three experimental filters. To date filters having standing water depths between 0.02 m to approximately 0.15 m have been effective. Filters having water depths of 0.025, 0.30 and 0.60 m were be built to determine the maximum allowable water depth. The Filters were numbered I, II, and III from the shallowest to the deepest standing water depth. The filters were monitored for bacteriological removals to determine if water depth effects biological development in the filters. Once removals stabilised the final rate of removals determined if water depth during pause times effected the removal capacity of the process. At the same time using the same raw water supply a COSS filter was operated to determine the differences and similarities between the processes. Bacteriological quality and head loss were monitored in this filter concurrently with the 0.30 m and 0.60 m SWD IOSS filters.

DO levels in the influent and effluent were monitored for each filter run for all filters and allowed oxygen utilisation rates to be estimated. This also was used

to characterise the development of the biological layer within the filters over time. The relative use of oxygen in the filters indicated the relative biological activity existing in each of them.

The change of oxygen content in the filter during pause times was evaluated by monitoring the oxygen content at the various ports at frequent intervals during the pause time. This provided data on the location of the biological layer in the filter and gave other estimates of oxygen utilisation rates by providing data on gradients and average dissolved oxygen in the supernatant

D3.0 Results and Discussion

Figure D.2 shows the massive and erratic fluctuations of removal efficiency of faecal coliforms. This figure only shows the last test after the filter was scraped the final time. These uncontrolled massive variations are the results of first, large variations in influent water quality second high flow rates, and the growth of bacteria in the filter due to the concentrated substrate existing in the spike which was collected in the filter skin. In addition the majority of faecal coliform indicators grown and spiked into the influent were the more robust and generally existing *Klebsiella sp.* rather than *Escherichia sp.* The *Klebsiella sp.* is able to grow at lower temperatures and it is speculated that enough substrate and a

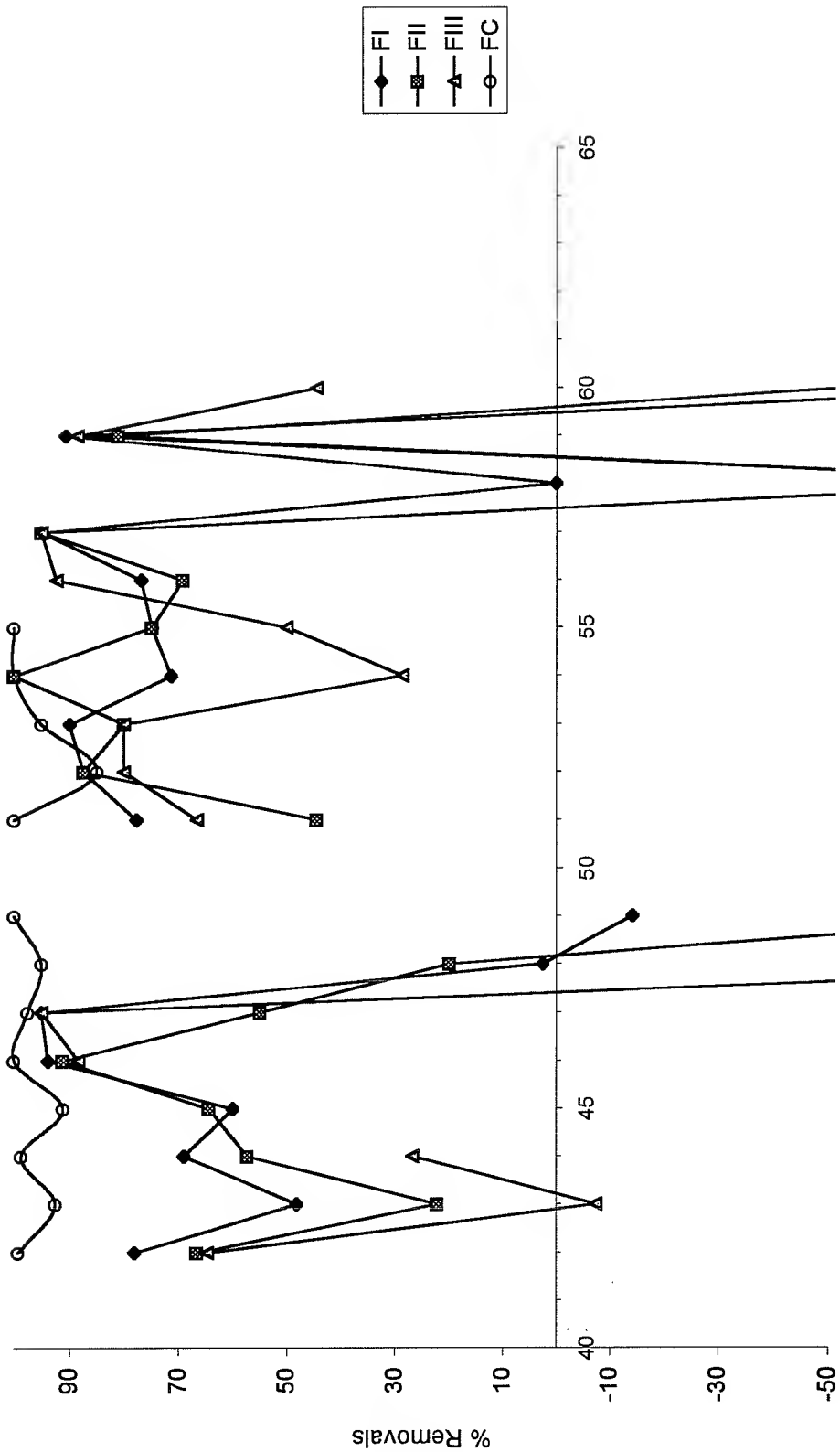

Figure D.2 Removal Rates over Time

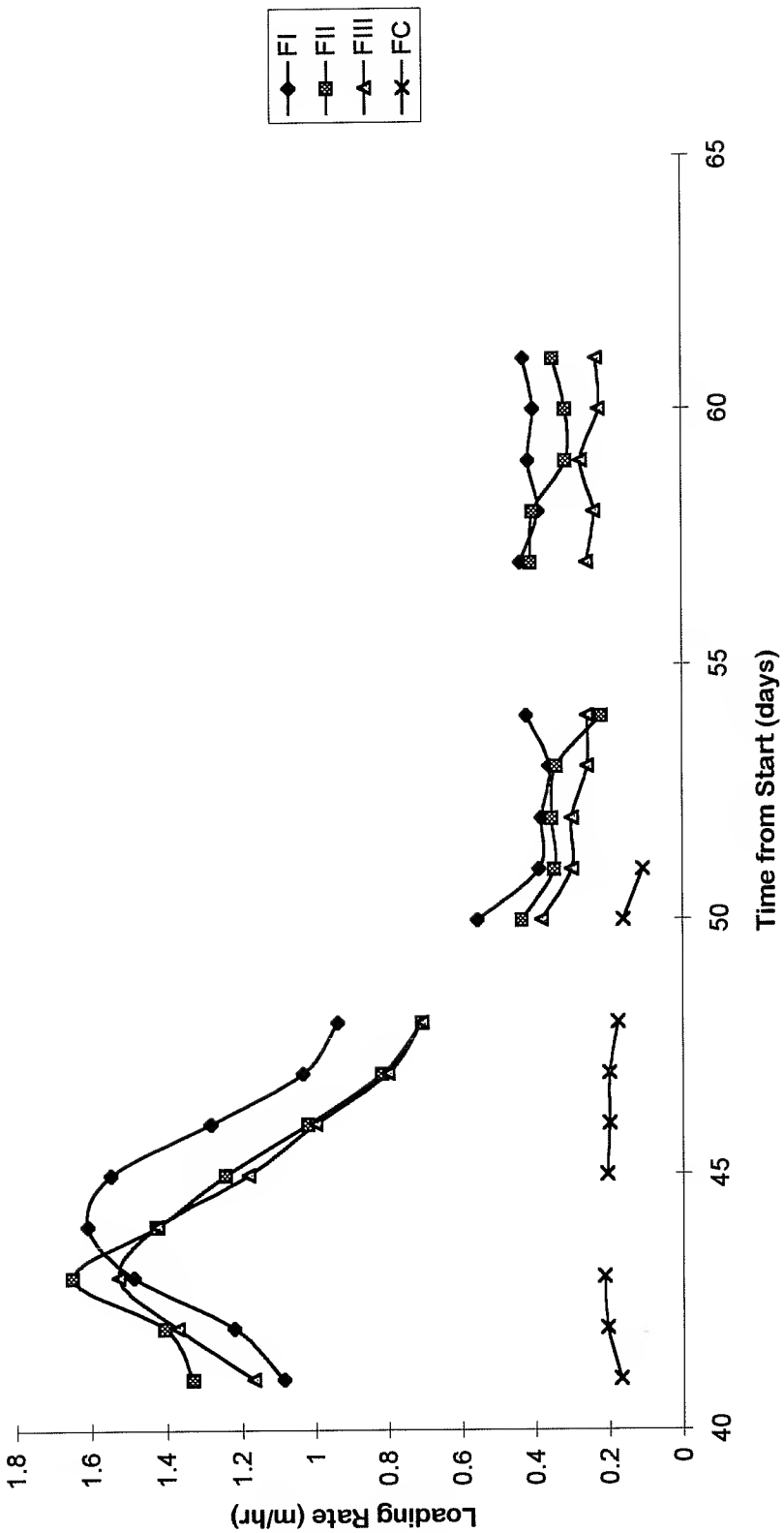

Figure D.3 Variation in Loading Rate with Time

sufficient temperature were present in the filter to allow the growth of these bacteria which produce a positive faecal coliform colony with the membrane filter technique and m FC media.

It is assumed that the variation in the influent was the major cause of the changes in removal efficiency since all three of the intermittently operated filters followed each other in there variations. Generally FI with a 0.025 m standing water depth had better removal rates than the others. The continuous filter did not seem to follow the other filters because the rate at which water flowed through is meant that the effluent sample was not water which had been replaced by the particular influent.

Figure D.3 shows the change in loading rate of the four filters during the last experiment. It is interesting to note the increase in loading rate over the first three days of the test and then its decline to a nearly stable level. The continuous filter is almost constant since the outlet valve was adjusted daily to keep the filtration rate near 0.20 m/hr.

Figure D.4 shows the massive fluctuations of the faecal coliform counts in the influent, filter I and the continuous filter. These are mainly responsible for the

fluctuating removal rates and show the need for the development of a stable water supply for testing water treatment processes.

Figure D.5 graphs the changing hydraulic conductivities of various section of the 50 cm sand bed going down through through the filter. It is clear that the first 5 cm of sand bed depth are responsible for the majority of the headloss through the filter.

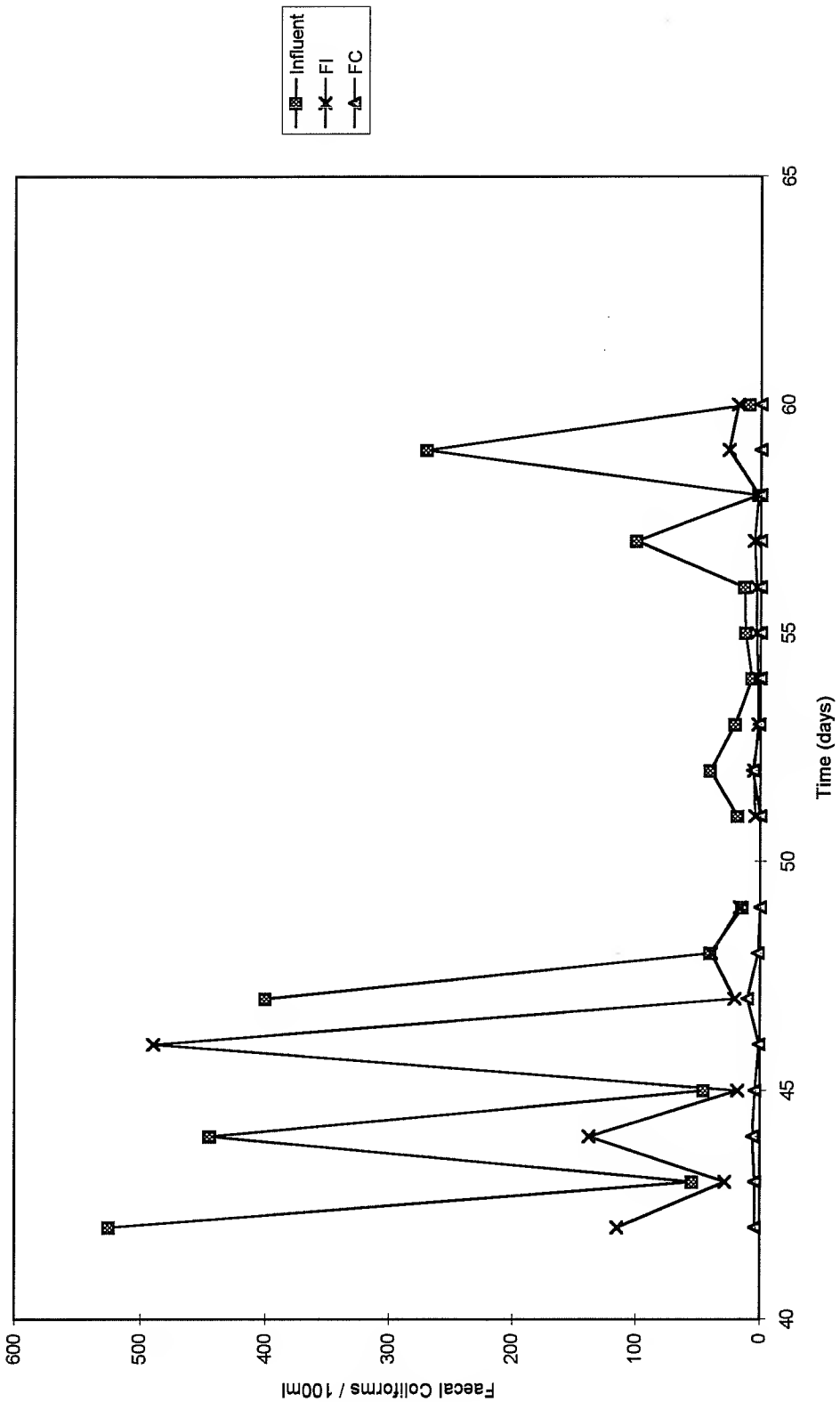

Figure D.4 Variation of Water Quality with Time

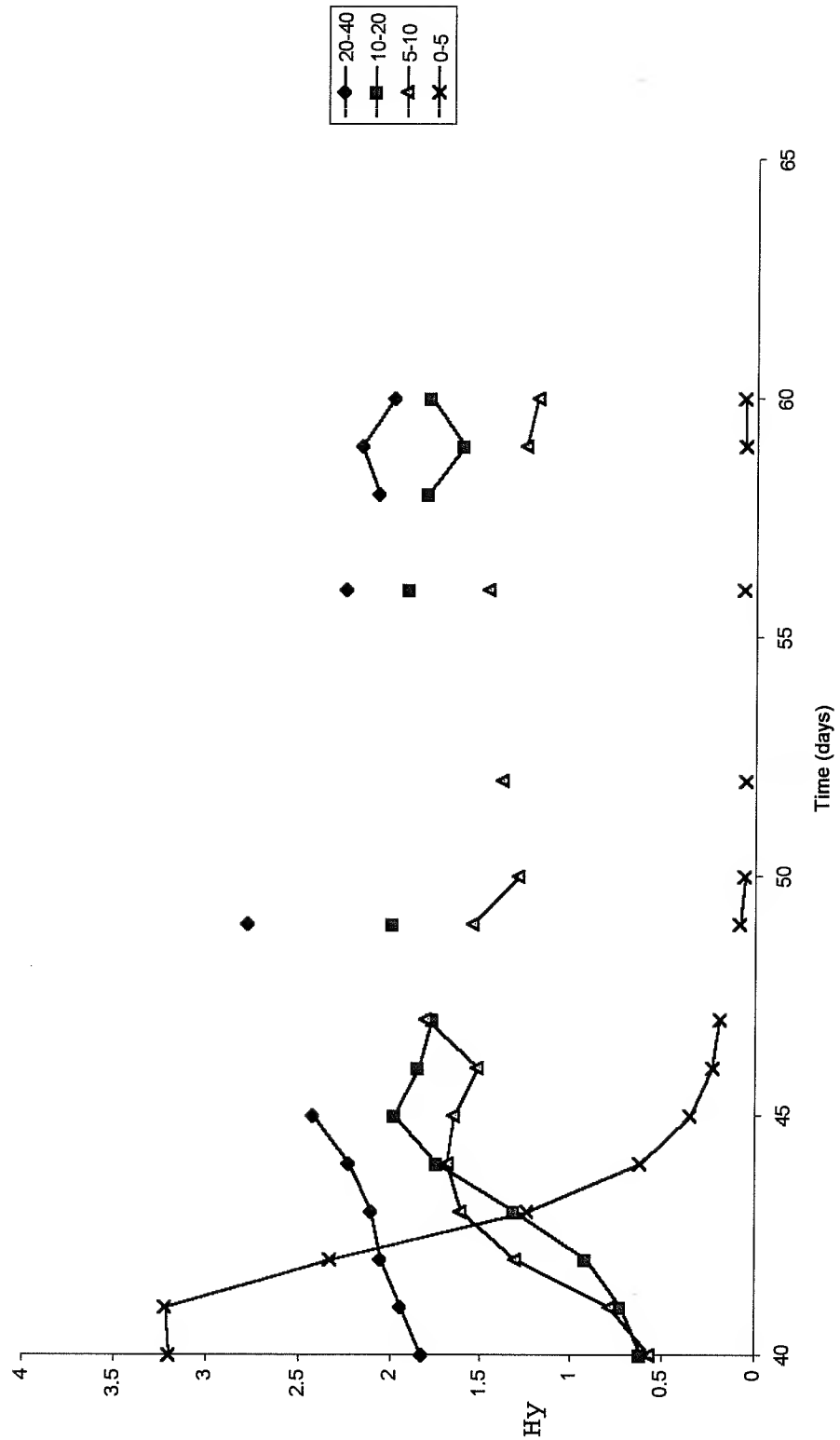

Figure D.5 Variation of Hydraulic Conductivities of Different Portions of The Sand Bed For Filter I

Appendix E

NICARAGUA COMMUNITY SCALE HOUSEHOLD FILTER PROJECT

(extensively extracted from Manz and Buzunis 1995)

E.1 IOSSF: Innovations in Design for Intermittent Operation

The final designs used in this study were developed over two years by testing and reviewing several prototype designs. Even now new design innovations are being tested to account for cultural variations and to improve the filters as a result of experience gained. Filter design has progressed along two main lines. The first is the plastic filter units designed for rapid installation, pilot studies as well as versions for commercial development. The second is the concrete designs which are meant to be simple enough to be built and installed on site by the communities themselves and to be exceedingly cost effective. The design development has been supervised by David Manz at the University of Calgary.

The original prototype filters were based on the original design reported by David Lee. These filters had a valve placed on the outlet and required supervision during operation. A modification of this design was used in the pilot study conducted in Nicaragua in 1993. This filter had two valves one on the outlet to allow filter water to be collected and another valve used to reduce the supernatant water level to the proper height after filtration. While these filters proved to operate very well in the field the operation was complex and there were problems with leakage and theft of the valves.

The use of valves on the outlet was originally implemented to allow the larger head between the water surface and the outlet to drive the flow giving a higher flow rate. After noting the problems with using valves in the field and the increased complexity of operation the water level control was changed to an overflow type. This significantly reduced the complexity of the filters and did not adversely effect users perception of flow rate.

For Nicaragua a concrete filter was developed because of the indigenous skill with concrete. Wash basins, barbecues as well as many other items are constructed of concrete. The concrete design went through several phases and finally resulted in the design used for this project.

E.2 The Canadian Water Filter Design: True IOSS Filters

IOSS filters used for households and small scale water treatment in developing countries includes two main design components which are critical to the proper operation of the filters. This design is also called the Canadian Water Filter Design. Although the filters may appear different true IOSSF will include these two components. The first is the diffuser plate or basin. The diffuser plate functions to protect the sand bed from disturbance when water is added to the filter. The diffuser plate in concrete filters is a concrete plate or tile with 6.5 mm holes in it through

which the water drips onto the water layer over the sand bed. The second is the water level control. This system of tubes functions to control the depth of water over the sand bed during resting periods using the typical overflow principle of continuous filters. The outlet tube is set so that a shallow layer of water is always kept above the sand bed. No valves or plugs are used to prevent water from being stored in the filter and a deep layer of water being kept above the sand bed.

The other components of the IOSS filter are the same as those used in COSS filter designs. That is a container, underdrain, sand and gravel. The containers for IOSS filters are normally in the order of 80 cm tall and have the surface area sized to provide the desired flow rate. The underdrain is normally a PVC pipe with 6.5 mm holes drilled in it at 2.5 cm intervals and packed in the gravel layer. The sand used in filters up to now has followed the normal guidelines used for COSS filter sand.

E.3 Field Installations and Conditions

In Nicaragua filters were constructed by two factories based on a full scale model constructed from a set of forms brought from Canada. The total capital cost of the filters was 163.00 Cordobas each or about $20.00 US. The factory producing filters in Managua continuously had difficulty with quality control and uniformity. Some of

these filters were modified after being installed to improve operations. The filters constructed in Nandaime were well within required specifications.

The IOSS filters installed in Valle Menier generally have the dimensions of the following sketch in Figure E.1. The surface area was calculated to give a flow rate of about 1 l/min at the expected loading rate. The height of the container was calculated allowing for a 10 cm gravel layer, 50 cm sand bed depth, a 5 cm standing water depth a height above the water surface to allow a 20 litre pail of water to be added to the filter with 5 cm of freeboard to prevent overflows. This gave a final height of 88 cm . The diffuser plate was located 2.5 cm above the water surface during pause times.

The gravel used for the underdrain was crushed 1/4 inch stone from a nearby crushing operation. The gravel was washed prior to being placed in the filters. The gravel underdrain of the filters was generally between 10 and 15 cm deep depending on the filter manufacture. About 0.01 m^3 of unpacked washed gravel was used for each filter.

Sand used in the filters came from a royo or seasonal river bed. This sand was also being mined for use in concrete factories. The sand was firsts sieved though a 2

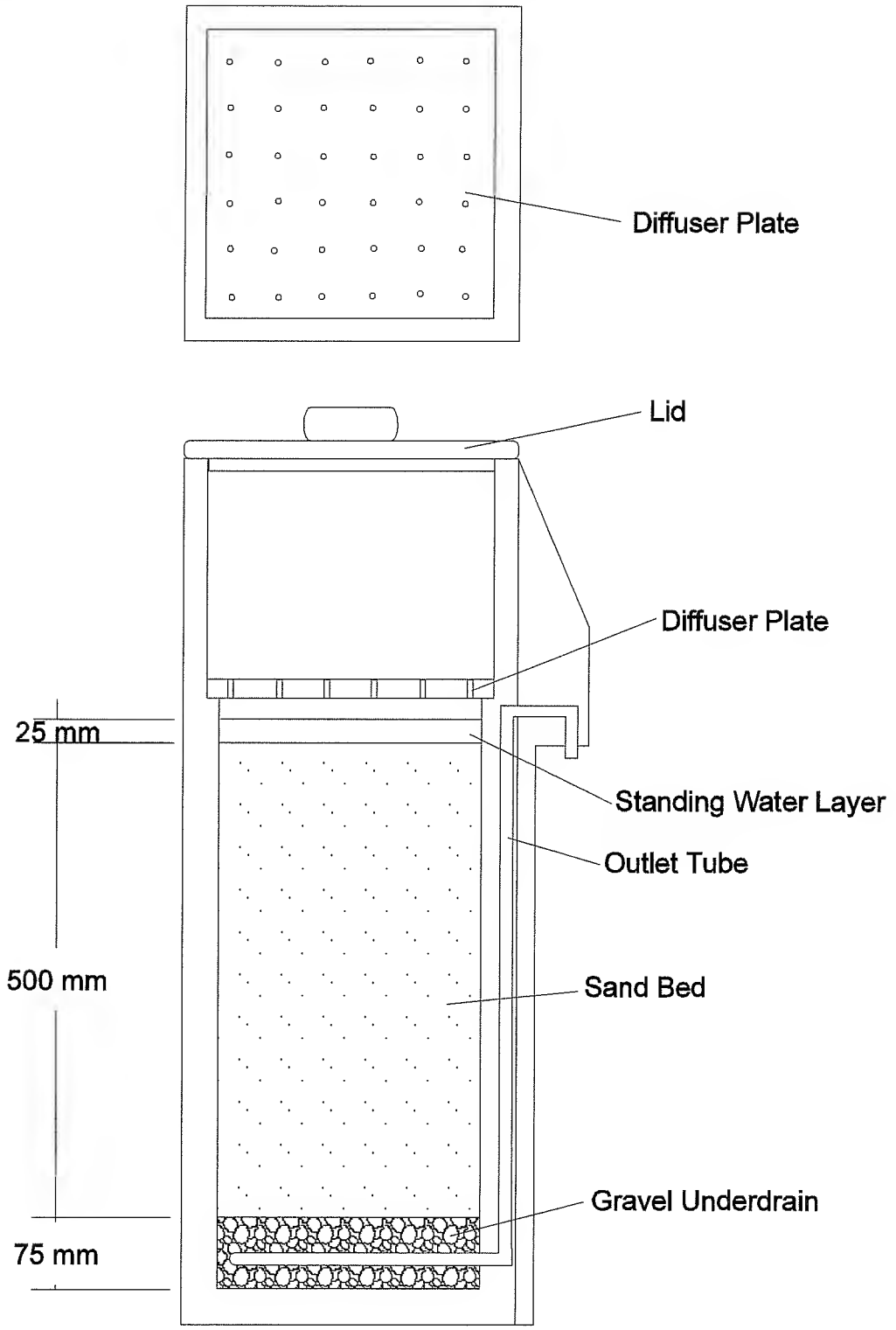

Figure E.1 Sketch of Concrete Filters Used in Nicaraugua

mm mesh to remove the larger grains and to remove any large organic mater. The sand was then washed to remove fine silts and clays before being placed in the filters. Each filter used approximately 0.04 m^3 of sand. This sand has a effective size of mm and a uniformity coefficient of well with the specifications for normal COSS filter sand.

E.2.1 *Filter Installation*

Each filter was installed following a basic format. First the filter was emptied of any material which may have fallen into it during construction or transportation. Next the underdrain was checked to ensure it was installed properly and the holes were oriented correctly. The empty concrete filter was then placed in the location and the base was shimmed and filled so that it was relatively level and sturdy. Next gravel was added until it covered the underdrain tube by about 5 cm. A 5 gallon pail of water was then added to prevent air from being trapped in the sand. The surface of the gravel layer was levelled and the sand was added to a depth of about 10 cm below the diffuser plate support and levelled. Next the diffuser plate was placed. Water was then run through the filter. Initially the water produced by the filter was cloudy but after 50 to 100 l of water had been run became clear. The amount of water needed to clarify the filtered water depended on the degree to which the sand had been washed..

E.2.2 *Project Site: Valle Menier*

Valle Menier is a rural community located at the site of an old hacienda in an area used for growing sugar cane. The community is approximately 6 km south of the city of Nandaime, Nicaragua. Valle Menier includes 56 individual families with 55 separate households. The population of the community at the time of filter installation was 326. This gives an average family size of 5.8 however the smallest household consisted of 1 person the largest included 13 members. The community is spread over an area of 4 km^2. A map of the community showing filter installations, water sources, roads and foot paths is included in Figure E.3. A total of 56 filters were installed in Valle Menier, 55 in households and 1 in the school. The community is served by more than 15 water sources. 7 shallow wells, 1 shallow well with a rope pump, 2 rivers, 1 irrigation well with a vertical turbine, 1 well outside the community and several infiltration galleries. This site was chosen for the project because of its size, number of water sources and accessibility by road.

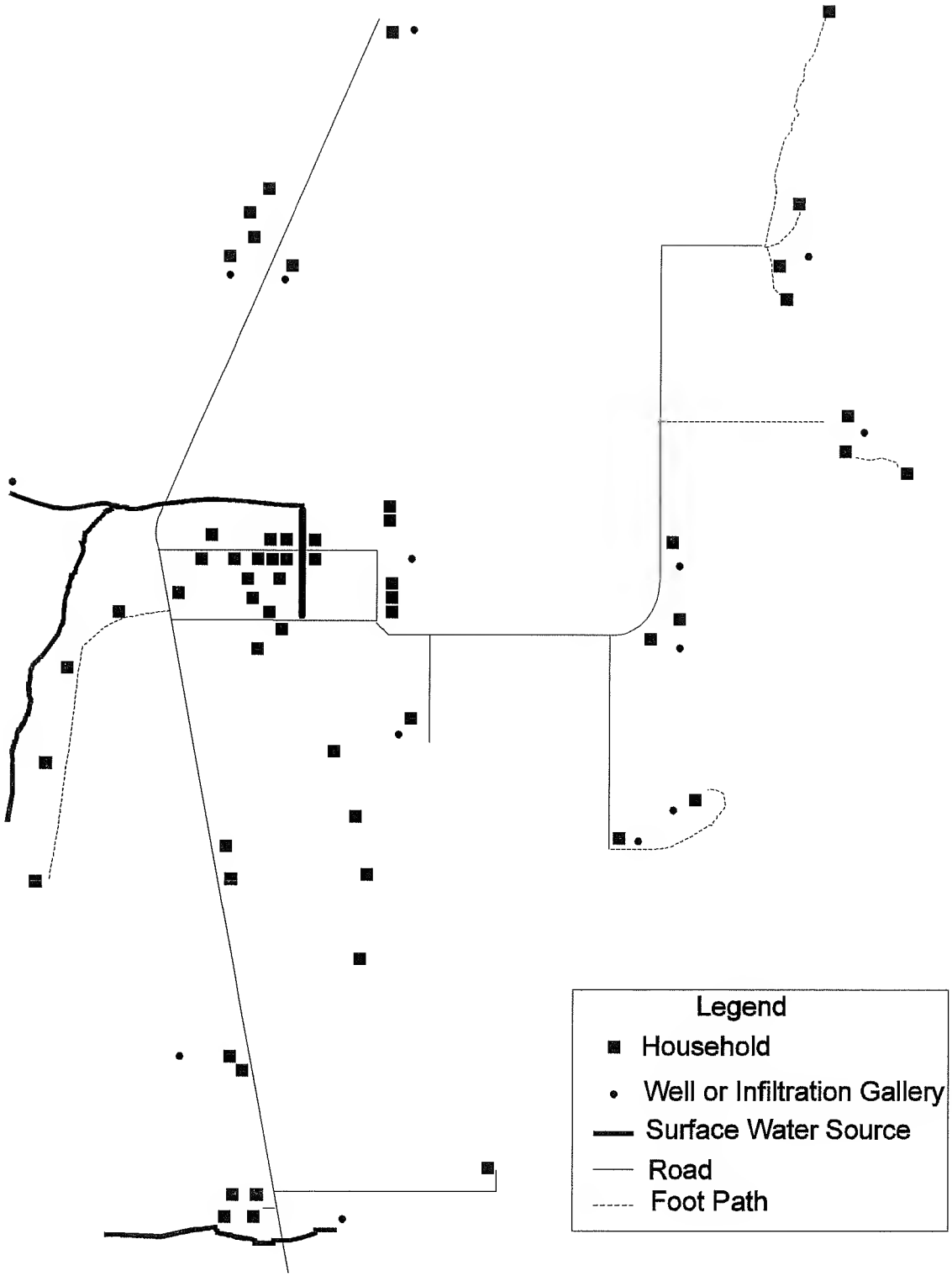

Figure E.2 Valle Menier, Nicaragua

Water use in Valle Menier was classified into two main categories. First water used for domestic animals, washing and watering gardens and second, water used for cooking and drinking purposes. Of total water use water used for cooking and drinking is only a small percentage. Because of access problems water used for cooking and drinking by an average family of six was about 40 litres a day. However, this varies by family size and the nearness of the water source. The amount of water run through the filter daily is important to the how quickly filter performance develops. Water was generally collected in the morning by women or girls and carried to the house were it was used throughout the day. In most instances water was carried a long distance, more than 300 m, over rough terrain.

E.3 Field Testing of Filter Performance

The establishment of a field testing program allowed a large number of filters to be tested using several water sources. Each filter can be considered a independent pilot plant with different operators. The objective of the field program was to confirm the effective operation of IOSS filters under actual field conditions. By using natural water sources many of the problems encountered in attempting to simulate a contaminated water source were solved. In addition anecdotal data was collected from filter users as to the observed and perceived improvements in water quality.

E.3.1 *Field Testing Program*

Once the filters had been installed a weekly visit and sampling program was established so that each source and filter was tested once per week for faecal coliforms and selected filters were tested for other parameters of pH, dissolved oxygen, electrical conductivity and temperature. Each filter had three faecal coliform tests performed and many had four, from June to July, 1994, provided a sample could be taken. The standard methods guidelines and world health organisation guidelines were followed as far as possible when testing for faecal coliform bacteria. However, the number of tests required as well as scheduled power outages of 8 hr. a day made the normal sterilisation of sample bottles and filtration apparatus impossible. Instead bottles and apparatus were immersed in boiling water for 20 min reducing the time required by 40 min and increasing the capacity of the laboratory because the autoclave was relatively small. It is suspected that this procedure was not as effective as sterilisation by pressurised steam. A follow up evaluation was conducted in November 1994, again time limitations did not allow all filters to be visited and tested.

E.4 Field Results

The following table, Table E.1, summarises the results of the field tests in Valle Menier. Removal Rates reported are the average of all tests performed after the filter had operated 21 days with a consistent water source. This is the time required for biological layer development reported by Husiman and Wood 1974. Between July 12 and 14 source 1 was repaired and improved. This had a significant effect on the bacteriological quality of the water from this source. A carry over or damping effect discovered in the more intensive laboratory testing showed that this data could not be used since it did not provide realistic evaluation of filter performance. Because of quality control problems with filters constructed in Managua some modifications were required on several filters. In these filters the resting water level was at the diffuser plate level. This provided only the surface area of the water in the diffuser plates holes for oxygen transfer and caused erratic results for these filters until several weeks after the diffuser plate was raised. After which the filters recovered. Filters requiring modifications and filters having been used with plugs and tests of filters using source 1 after the 14th of July are not included in these averages.

Considering the variability of operators, water volumes, environmental conditions as well as inaccuracies associated with the field testing the range of removal rates from a low of 86.67% to a high of 100.00% with an average of 97.00% is excellent.

Table E.1 Average Removal Rates of Faecal Coliforms for Filters In Valle Menier, June-August 1994

Filter #	Removal Rate %	Filter #	Removal Rate %
6	100.00	11	100.00
12	99.42	15	99.17
16	96.83	20	86.67
22	89.92	24	100.00
26	99.83	28	100.00
30	95.61	31	98.94
32	95.74	33	95.32
34	99.68	35	94.82
37	97.73	38	100.00
39	98.85	40	99.87
41	99.92	43	98.00
44	99.52	45	96.29
46	98.68	47	97.35
48	95.83	50	88.17
52	97.75	53	94.92
54	98.00	56	94.85
57	93.20	Average	97.00

In fact this value is far in excess of results obtained in experiments which operate continuous slow sand filters intermittently.

After 2 months a follow up evaluation of the filters was performed which included turbidity tests. As result of a lack of commitment by the local government proper education and follow up had not been done for the community scale project and so many filters were no longer being operated properly. In addition, many more households had been changing water sources from the wells to closer surface water sources and would not reliably report these changes since it was perceived as very undesirable to use anything but the nearest well. Unfortunately this resulted in unknown spikes in the influent and did not allow the actual filter performance to be calculated. The results of the properly operated filters using consistent sources during the follow up evaluation are included in Table E.2.

As with the previous data properly operated filters on average remove more than 96.4% of influent faecal coliform bacteria. The turbidity test also show a high percentage removal although not as large since much of the water is relatively turbidity free well water. The above table shows the data for all filters which were tested and being operated correctly.

Table E.2 Faecal Coliform And Turbity Removals of Properly Operated Filters in Valle Menier, Nicaragua, November 1994

Filter #	Removal of Feacal Coliforms %	Removal of Turbidity %
3	100.0	86.1
6	96.4	
7	97.5	62.2
8		99.2
10	99.6	40.0
11	96.5	
16	96.8	76.2
18	99.0	62.5
23	95.5	
24		74.9
25	85.5	81.3
26		73.5
32	100.0	89.8
33		65.0
35	100.0	89.1
38	100.0	58.3
39	100.0	
40	90.0	60.9
47		90.3
52	88.0	75.0
56	98.0	62.8
Average	96.4	

In addition to the actual faecal coliform and turbidity measurements anecdotal evidence was collected for the filters. In all cases were the filter has not been decommissioned due to miss use or exceptional circumstances the filters are accepted and perceived as providing great benefits. When a toad died in the main well and caused a bad smell and taste in the water there was enough confidence in the filters to switch to a nearby stream having a turbidity of more than 50 NTU and a faecal coliform count greater than 2000, the contamination of this stream is estimated to be in the order of 10000 colonies/100ml. Unfortunately the community had switched back to the well but in many instances the carry over effect was still present preventing evaluation of filter performance. Water is reported to look, smell and taste better. Additionally families using the filters perceive a reduction in the incidences of dysentery and diareha. Communities surrounding the project community of Valle Menier have requested filters be installed in their communities and have made inquires as to how they can be obtained. During the pilot studies in Honduras and Nicaragua, were pilot filters were installed in separate households, several neighbouring households would carry water more than a kilometre to be filtered. In one case the filtered water was considered to taste so much better that the man owning the filter had to take three times as much water to work with him because his co-workers would drink it. In several instances owners of the filter have referred to the filter as "*un gran cosa*"; or a great thing. (Household Residents, 1994)

The greatest piece of anecdotal evidence for the effectiveness of the IOSS filters installed in Valle Menier is that this is the only community in the region without cases of Cholera (Orozco 1994).

E5.0 References

Household Residents (1994) personal communication, Residents Valle Menier, Nicaragua

Orozco, N, (1994) personal communication, Director of Hospital, Nandaime, Nicaragua